Just Build It! A Fully Functional Concept Vehicle Using Robotic Wheels

by Peter Schmitt

Akademiebrief, Diploma in Fine Arts,
Kunstakademie, Academy of Fine Arts, Duesseldorf Germany, 2005

Meisterschuerler of Professor Klaus Rinke,
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Submitted to the Program in Media Arts and Sciences,
School of Architecture and Planning in partial fulfillment of the
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Author
Program in Media Arts and Sciences,
May 11, 2007

Certified by
William J. Mitchell, Alexander W. Dreyfoos Jr. (1954) Professor of Architecture and Media Arts and Sciences, Director, Smart Cities Group, MIT Media Laboratory
Thesis Supervisor

Accepted by
Andrew B. Lippman
Departmental Committee on Graduate Studies, Media Arts and Sciences

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Abstract

Interest in electric vehicle drive units is resurging with the proliferation of hybrid and electric vehicles. Currently emerging key-technologies are: in-wheel motors, electric braking, integrated steering activators and active suspension combined with embedded sensors and real time computation. These electric vehicle drive units have the potential to go beyond current applications and lead to a novel vehicle architectures and a new vehicle culture.

Building upon the research in the Smart Cities Group at the MIT Media Lab I propose to implement a novel mechanical and electric robotic wheel technology and the associated control and drive software in a fully functional concept vehicle. I will make use of a modular design for wheel robots which I developed through prior iterations at different scales combined with applied automotive technologies. This platform provides a realistic and scalable test-bed for evaluating the proposed technologies and will ultimately serve building a full scale concept vehicle.

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Reader *Frank Moss*
Director,
Professor of the Practice of Media Arts and Sciences Jerome B. Wiesner
Professorship of Media Technology

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Introduction

Wheels: Mundane But Functional

Was the road designed for the wheel or the wheel designed for the road? The evolution of the wheel is inextricably linked to the development of roads: 2000 years ago, roads were being pounded by wheels reinforced with iron belts. 200 years ago, wooden wheels were fitted with bearings and suspension as well as hard rubber exteriors instead of iron belts to reduce the impact on the road and improve the comfort in the vehicle. Today's light metal alloy, super-grip rubber, high performance suspended car wheels hardly leave an impression on the road. The estimated investment humankind has made in improving the wheel and its ideal roadbed are staggering and probably make the wheel one of the most expensive mobility devices ever developed (perhaps more expensive than man traveling to the moon?). This thesis describes a design development for a new type of wheel design that may have important implications for the next episodes in the historical sketch described above.

Wheels on Cars

Though obvious, the fundamental characteristic of wheels is their round nature which makes them suited for providing mobility. Within an automobile wheels have a specific role which extends this basic function. Wheels provide the contact patch between vehicle and ground and they are the "last" component in the propulsion system. Drive or braking forces applied to the wheel in combination with the contact patch determine the accelerating and decelerating properties of a vehicle as well as its ability to stay on track or corner without slipping. The contact between vehicle and ground needs to be maintained at all times, especially on rough terrain. The suspension was designed for this purpose, but the wheel itself is an important part of the suspension. The deformable air filled rubber tire compensates for small bumps or the initial impact before the suspension reacts. The overall wheel diameter and the proportion of the rubber tire also affect vehicle suspension. And last but not least, wheels steer the vehicle by changing their relative position to the car body.

Vehicle Propulsion Systems and Vehicle Architecture

Vehicle propulsion systems have developed over time. In the early days of the automobile, both internal combustion engines (Internal Combustion Engine hereafter as ICE) and electric engines were in use (Ref. 11). And in fact, the electric motor was more popular due to its effortless operation, low noise level, and easy maintenance. It was also generally perceived as a “clean” vehicle because it lacked an exhaust.

By the 1920s, however, energy storage capability had led to the triumph of ICE vehicles. In a minute or two, drivers could refill their car with dozens of kilo-watt hours to power their car across great distances at high speeds. Battery technology was far behind by comparison.

The shift to ICE vehicles impacted vehicle architecture as a whole. As the term “internal” states ICE vehicles have one central and embedded propulsion force creating rotational shaft work which is transmitted TO THE WHEELS. This vehicle architecture became a paradigm which is still valid. Purely electric vehicles used hub mounted motors IN THE WHEEL that were easier to handle and more efficiently translated force the wheels (Fig. 1).

Over time, hub mounted electric motors have degenerated into an electrical assistance and starter motor for the internal

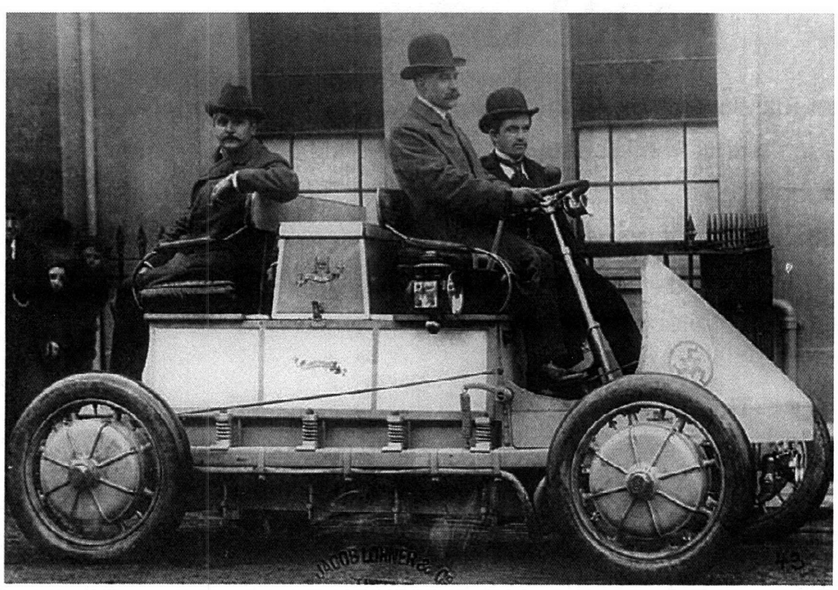


Fig. 1, Semper Vivus, 1900 by Lohner and Porsche, hybrid vehicle with in-wheel motors (Ref. 1)

Fig. 2, General Motors EV1 (http://ev1-club.power.net/evpics.htm)

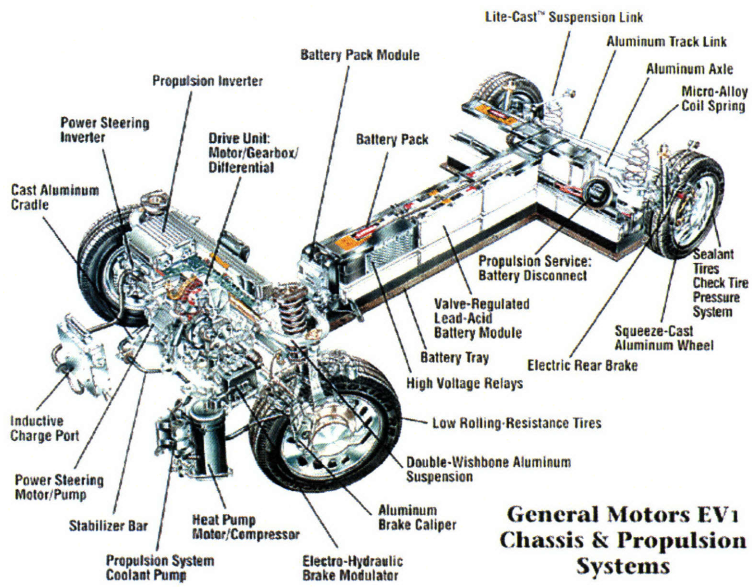


Fig. 3, Mini Cooper modifyed by PML equiped with „yellow“ in -wheel motors (Ref. 14)

combustion motor. Today's hybrid vehicles utilize more powerful electric drive motors, but stay within the same scheme by embedding the electric motor like and ICE (Fig.2). Even the renaissance of hub mounted electric motors in some purely electric and hybrid cars has not led to a fundamental rethinking of vehicle architectures (Fig.3).

Thesis Outline

This thesis researches how a novel type of modular vehicle drive unit can be successfully adapted to car wheel design and lead to a different kind of vehicle architecture. The proposed interchangeable units will be capable of driving, braking, suspending and steering different types of vehicles using electric activators. They will communicate not only with the vehicle, but also with each other to address certain driving situations autonomously. For example, maintaining contact with the ground under all circumstances or calculating individual speed and angle settings during cornering. Augmented with sensors, activators and a certain amount of intelligence these units automate transportation, a basic human need, and thus deserve to be called **wheel robots**.

I will introduce precedents and related research in the first Chapter. The design development process across several iterations at different scales will be described in the second chapter. I will address vehicle and system related aspects in chapter 3 and review the whole design process focusing on future directions in chapter 4.

Chapter 1: Precedents

MIT Media Lab

MIT Media Lab, Smart Cities Research Group

The Smart Cities Group at the MIT Media Lab with William J. Mitchell as Principal Investigator is a collaborative environment where students, researchers, and professionals are studying mobility and transportation concepts (Ref. 7, 8). Over several years, a shared knowledge base has developed which encompasses concepts for mobility within and outside the city such as: a modular vehicle architecture, pure electric city cars and shared-used city vehicles. Several members of the group have specifically focused on the impact of a modular architecture on vehicle design.

Cars today are extremely complex due to their many sub-systems which allow them to perform high-level functions reliably in one compact device. ICE, drive train, gearbox, electrical systems, climate-control unit, computational systems, networking devices, passenger compartment, trunk and more components form the overall vehicle. The car body has also evolved into a highly sophisticated piece of engineering in its own right that fulfills multiple functions including stability and safety.

The Smart Cities group analyzed the components of today's cars and questioned their current arrangement. By relocating elements closer to their functional space new arrangements and combinations of functions emerged, most notably the wheel robot. These units contain all the parts needed to propel the vehicle and can be attached to different kinds of vehicles through a standardized structural, electric and data signal. The approach brings together many existing technologies for wheels such as in-wheel motors and integrated steering actuators. In-wheel motors have been researched extensively and are currently experiencing a renaissance with the development of hybrid and electric cars (Ref. 3,19). Steering actuators have been placed within-wheels for fork lifts and buses (Ref. 4). And in-wheel suspension and modularity is a well known principle for platforms carrying heavy loads. Combining all theses aspects into one unit and proving its feasibility for the private vehicle sector constitutes the innovative approach introduced by the group.

The wheel robot supports a modular vehicle architecture which significantly reduces constraints on vehicles designers and engineers. Vehicle fabrication and assembly will become easier, more efficient and cost effective. Vehicle operation will also benefit from low-maintenance wheel robots. Even vehicle culture can evolve to include notions of customization and adaptation.

Kuenzler's Approach

Patrik Kuenzler, a researcher within the Smart Cities Group developed the first, hubless design for a wheel robot in 2004. It allows for the motor to remain stable while the rim, tire and wheel bearing are unsuspended (Fig. 4). The suspension travels vertically along two shafts. A third shaft transmits the drive force via a gear which slides on the shaft's triangular cross section. Kuenzler's design uses a hubless wheel bearing which makes the center of the wheel available for other components. At this point, the prototype does not include steering, braking, frame

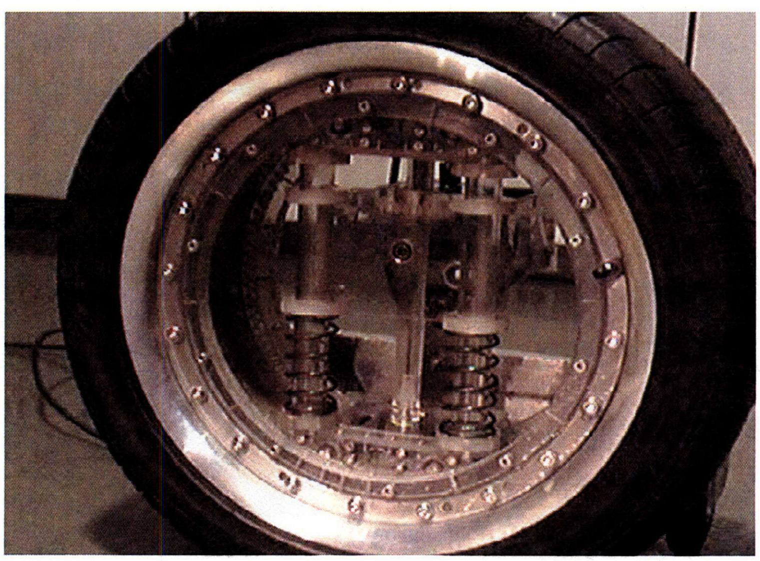


Fig. 4, Wheel robot by Kuenzler (Patrick Kuenzler, 2004)

connection and control electronics.

Other Precedents

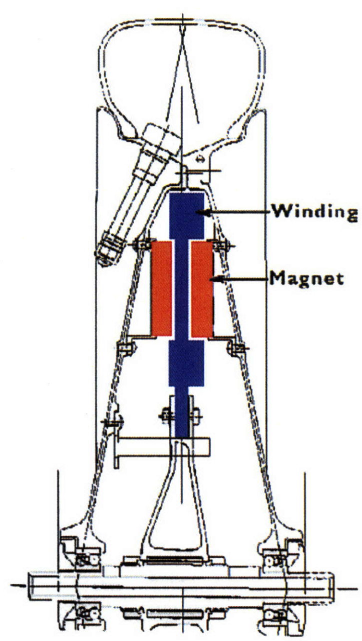
Although electric vehicles did not win the battle with ICE cars there have been significant technological advances for electric vehicle drive units and in-wheel drives since they were first introduced 100 years ago (Ref. 11). These developments have roots in diverse areas because electric vehicles have not been the focus of mainstream automobile research. Instead, solar racing research centers and automobile industry suppliers with advanced research facilities have been the key innovators.

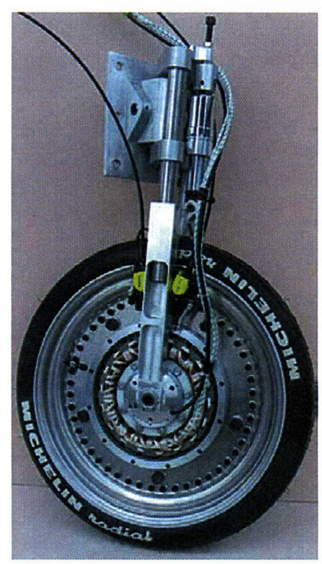
Solar Race Vehicles

The solar race vehicle challenge has improved electric vehicle performance overall.

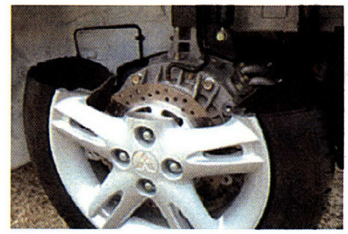
Engineers integrated new electric motor technology (Ref. 12) into their solar race vehicles. Experiments with in-wheel motors have led to solar race vehicles that can compete with ICE cars on performance criteria such as speed and distance. (Fig. 5).

Fig. 5,
left: Solar race vehicle in-wheel motor section drawing,
right: Solar Race Vehicle in-wheel motor
(Ref. 12)





Mitsubishi



Mitsubishi is one of the first large automobile manufacturers to include the same technology in their passenger car Colt EV which is part of a series called Mitsubishi In-wheel Motor Electric Vehicle (MIEV). (Fig. 6)

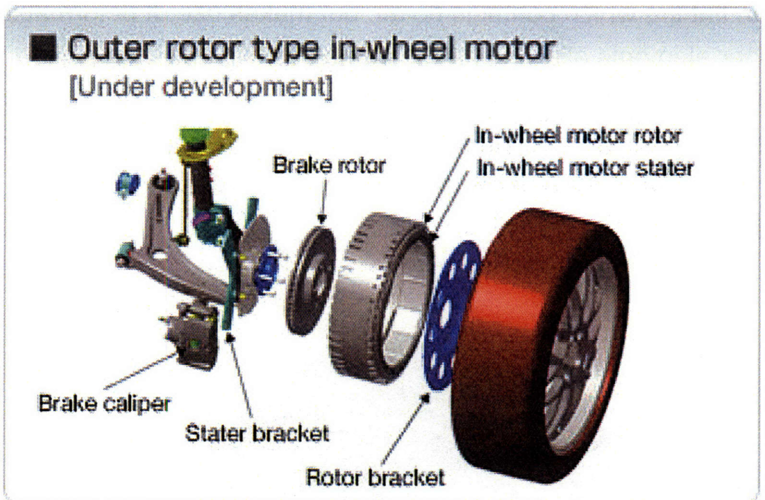


Fig. 6,
left: Mitsubishi in-wheel motor explosion diagram,
top: Mitsubishi in-wheel motor, early prototype
(Ref. 14)

Michelin and Siemens

Some more sophisticated developments are being undertaken by Michelin and Siemens. In both companies, engineers aim to include as many drive related components

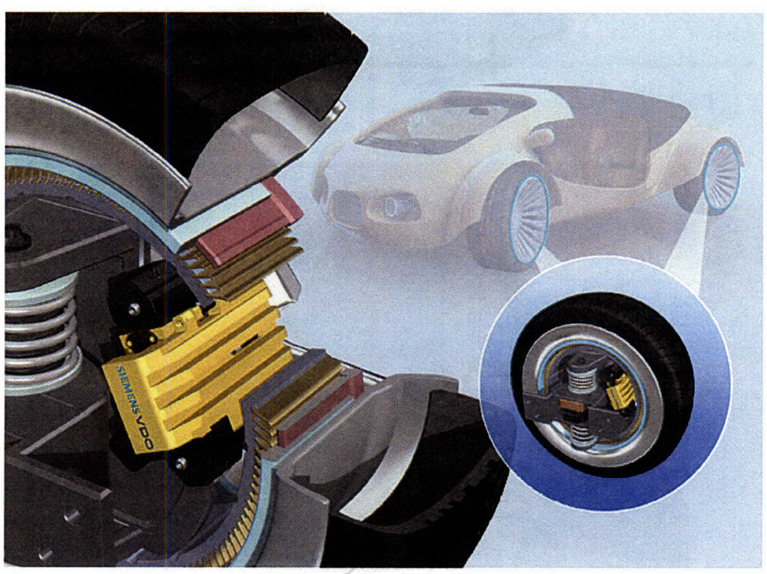


Fig. 7, Siemens E-Corner Concept, using the electronic Wedge Brake developed by Siemens
(Ref. 18)

in the wheel as possible. The Siemens E-Corners makes use of the Electronic Wedge Brake, a pure electronic brake caliper developed by Siemens. A linear motor is built around the brake and suspension unit to drive the wheel (Fig. 7).

The Michelin active wheel (Fig. 8) consists of a traction motor to drive the wheel, a disc brake and caliper and all suspension components forming an active suspension. Michelin has also developed a related technology called Tweel (Fig. 9). It is a run flat tire which contains no air, but makes use of deformable rubber elements allowing for the same stability and suspension performance as an inflated car wheel. The Tweel is tested and has been used in construction machines and sports gear. In Chapter 2, I will discuss the benefits of combining Tweel technology with wheel robots.

Fig. 8, above and right: Michelin Active Wheel (Ref. 13)

Fig. 9, Michelin Tweel (Ref. 13)

Chapter 2: Design Development

Wheel Robots and Their Constraints

Even though wheel robots reduce the constraints on vehicle architecture they have very specific constraints. The two most important factors are accommodating additional mass in the wheel and finding space for many more components than typical for a wheel.

Unsprung and Rotational Mass

Fitting more components into the wheel raises the question of the unsprung and rotational mass. The unpsrung and rotational mass describes the mass of the components (tire, rim, hub, and disk brake) which travel vertically during suspension. In most cases, adding components to the wheel increases the unsprung mass and destabilizes the vehicle. Specifically, the relationship between the moment of inertia of the unsprung mass and the suspension force changes. When the unsprung mass increases it takes longer for the suspension to regain ground contact after overcoming obstacles on the road.

There are two distinct approaches to minimizing the effects of additional unsprung and rotational mass. The first approach adjusts the suspension (damper, geometry, connection to vehicle) to compensate for the additional mass in the wheel. Another approach is to reduce the unsprung and rotational mass as much as possible. As shown in the work of Patrik Kuenzler, stabilizing the motor and making it independent from the wheel suspension movement is an alternative to the hub mounted motor.

Components

In addition to addressing the impact of additional unsprung and rotational mass in the wheel, the proposed wheel robots must integrate suspension, steering, braking, control and drive electronics and a connector into or near the wheel. Despite accommodating all these functions a wheel robot should be not exceed the motion envelope of a wheel inside the car body in size.

There is also an opportunity to place some components in the space between the wheel and the chassis.

Robot Wheel 1: Electric Bike

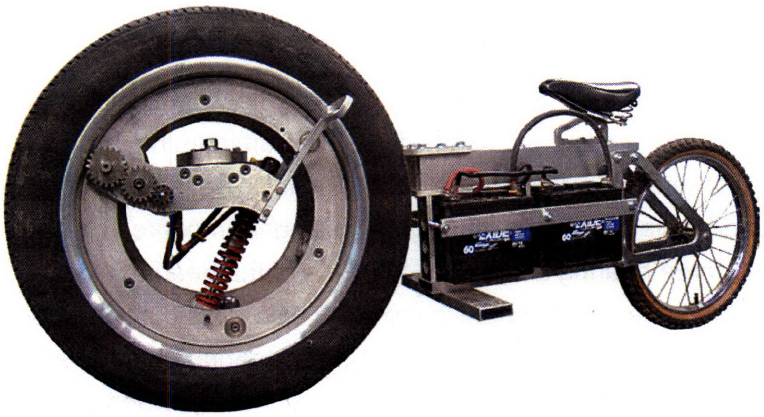


Fig. 10, top and left: Electric Bike

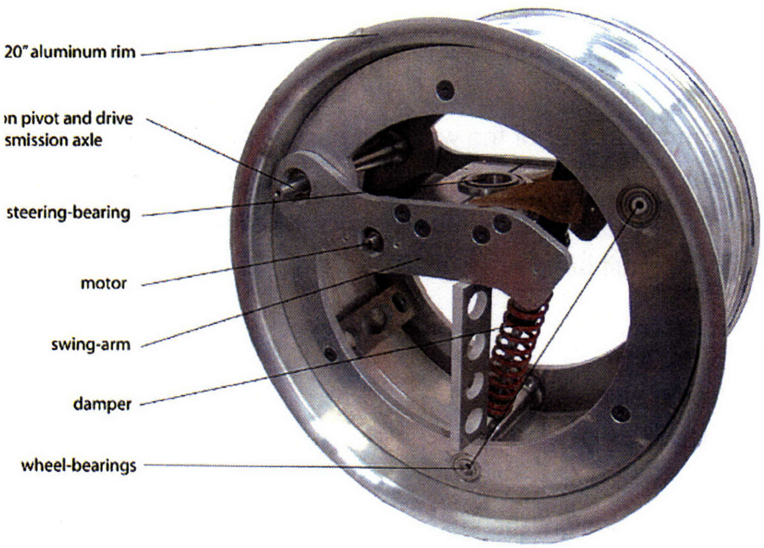


Fig. 11, Wheel Robot 1 with labled components

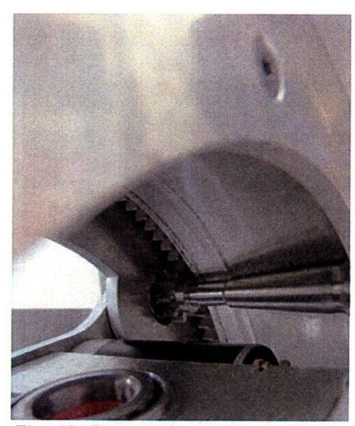


Fig. 12, Suspension rotation and drive force transmission axle, planetary gear ring

The first wheel robot design iteration addresses the first constraint of wheel robot design introduced above: reducing the unsprung and rotational mass. In this hubless design, the drive force is transmitted through the suspension. This method allows the motor to remain stationary (i.e. sprung) while only the rim and the tire are in motion.

Design Description

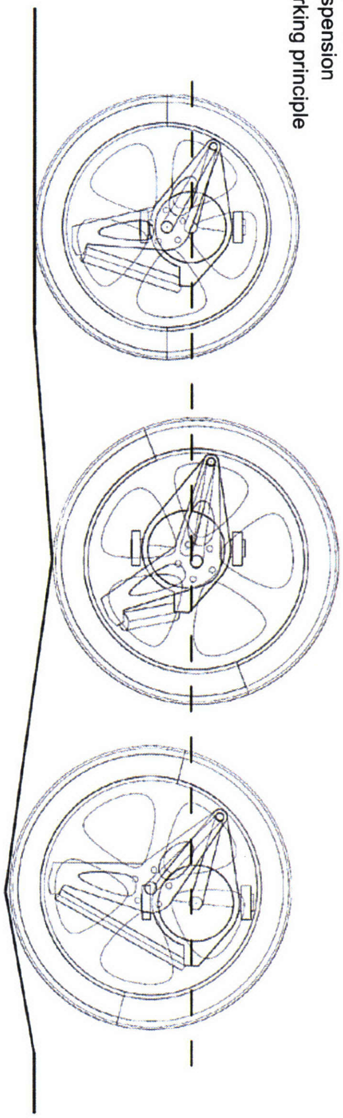


Fig. 13, Suspension working principle

This wheel robot design places the suspension between the unsprung components (tire, rim, and hubless wheel bearing) and the sprung components (motor, steering, activators, electronic and frame connection) (Fig.11, 13). A 20” aluminum two-piece rim serves as the backbone of the unit to which the other components are adapted.

The wheel bearing at the center of the wheel is replaced by three axles riding on the inside of the aluminum rim profile. One planetary gear ring is welded to the inside surface of the rim and drives the wheel through a small gear mounted on one of the three bearing axles (Fig. 12). One of the bearing axles also servers as the suspension rotation axle. This configuration supports transmission ratios of 10:1. The steering bearing is placed in the center of the wheel and is activated through handles placed at the outside of the wheel. Between the unsprung and sprung components of the mechanism an oil piston damper allows for as much suspension travel as a normal vehicle requires.

The bike frame connects from the side to the steering bearing in the center of the wheel. It carries the battery, the rear wheel and provides a seating possibility for the driver. The batteries are connected to the electric motor inside the wheel through a circuit breaker (Fig. 10).

Discussion

Fig. 14, Test Ride

In this design, the suspension swing arm axle allows for transmitting the drive force through the suspension to drive the wheel. As a result, the drive force does not interfere with the suspension. To achieve this goal, I use a swing arm rather than a vertical traveling suspension as designed by Kuenzler (Fig.11).

The hubless wheel robot design creates a huge space at the center of the wheel that can be used to place additional components like drive electronics and activators and especially the drive motor. The side connector makes it easy to imagine how it might be implemented in a vehicle.

This design was used to drive an electric bike built in 2004. Several test runs with the electric bike have shown the benefits of the design (Fig. 14) and also revealed the braking abilities of the electric motor.

Wheel Robot 2: One-Wheel Athlete

The one-wheel athlete is a platform for testing a novel vehicle architecture which demonstrates the importance of wheel robots for unconventional vehicles. The design is based on the athlete vehicle concept (hereafter referred to as "the athlete") by Axel Kilian and Mitchel Joachim, Patrik Kuenzler and Peter Schmitt in 2005 (Fig. 15, Ref 8). While today's trend of developing and refining sports cars only focuses on increasing the horse power and increasing the driver's comfort level, the athlete puts forth a different paradigm for sports cars.

The Athlete Vehicle Concept

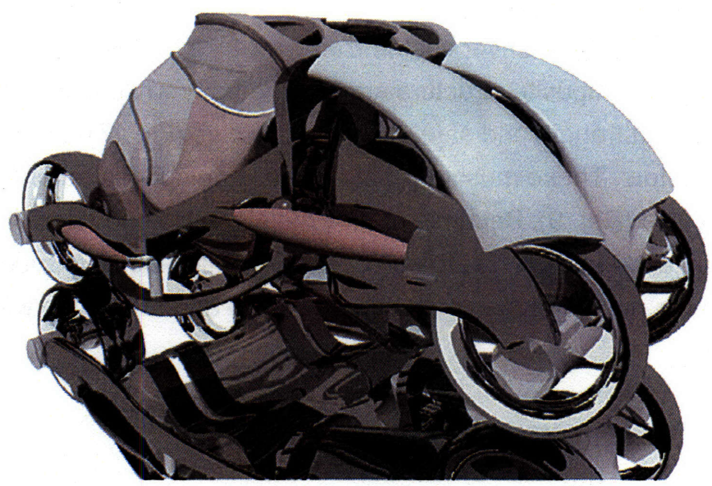


Fig. 15, The Athlete, 2005, by Axel Kilian, Mitchell Joachim, Patrik Kuenzler, Peter Schmitt (Axel Kilian, 2005)

The athlete's architecture enables it to perform synchronously with the driver's body as a control input. It is an extension of the body and connects it through the vehicle with the road. The athlete is built as an organism out of muscles, bones and skin and it's eight degrees of freedom allow for experiencing the road in a never know way (Fig. 16). It is a two seated car which bends in the middle for steering while the curve inner half of the vehicle moves in front of the curve outer half. At the same time all vehicle parts lean into the curve while both half's of the vehicle arch independently in order to remain ground contact of all four wheels. The seat is a kind of a harness or a wearable piece of furniture which supports each part of the human body separately while allowing for full body movement. Spring loaded joints counteract the body weight and crate a kind of zero gravity feeling for the driver. The body motions can be mapped to the

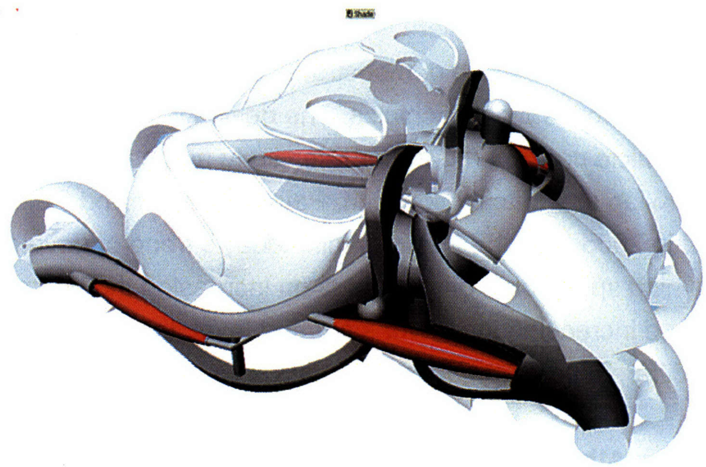


Fig. 16, The Athlete, Design by Axel Kilian and Peter Schmitt, indicating the muscles in red (Axel Kilian, 2005)

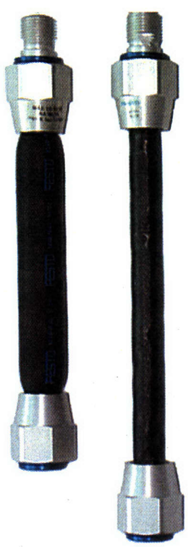


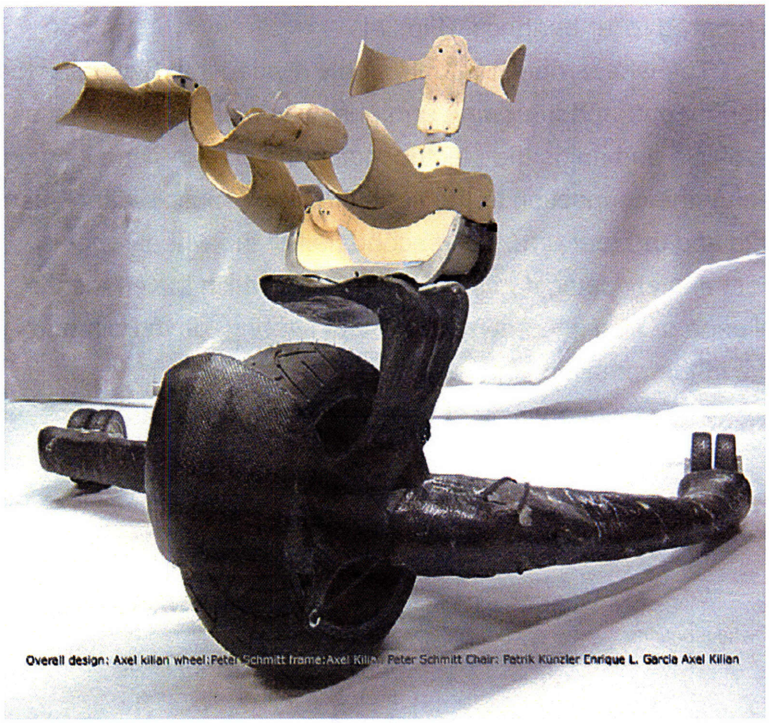
Fig. 17, Festo, Fluidic Muscle

vehicle motion in a driver customized way. Like bones, a fiber reinforced composite structure shapes the body while assuring the necessary strength and safety. Fluidic muscles (Fig 17)) are used as actuators. These muscles contract while being inflated or filled with a fluid (Ref. 9). Because of the whole vehicle body bending, arching and flexing it has to be covered by a flexible skin under which the motion of the contracting muscles and the bones will be visible.

Fig. 18, ... „Riding The Wheel" in-speration for the One Wheel Athlete

The One-Wheel Athlete Design

As a proof of concept the athlete vehicle was narrowed down to its core components inspired by the idea of riding the wheel (Fig. 18). This one-wheel athlete version consists of one wheel and one athlete seat attached to the wheel supported by a v-shaped frame in the back (Fig.19, Ref 10). The driver's motion is still controlling the vehicle while at the same time the driver follows the motion of the wheel to which the seat is attached.



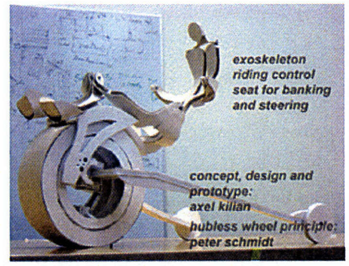


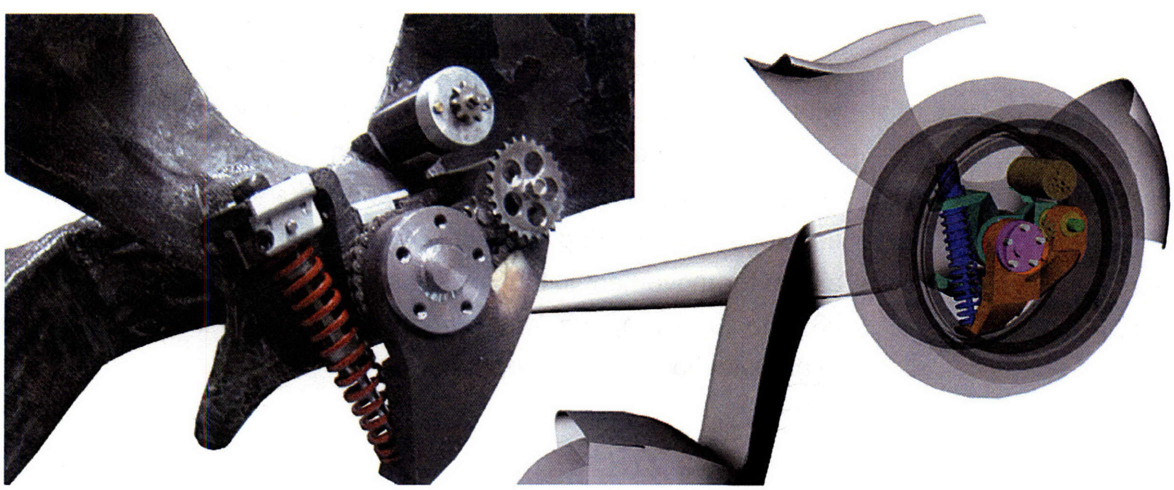
Fig. 19, The One Wheel Athlete,
above: developed by Axel Kilian
left: final vehicle by Axel Kilian,
Patrik kuenzler, Enrique Garcia and
Peter Schmitt

In collaboration with Axel Kilian, Enrique Garcias and Patrik Kuenzler a full-scale working prototype was designed and built. I contributed to this prototype by designing and building the wheel robot.

A Hubbed Wheel Robot

Like the electric bike the second wheel robot design iteration uses a swing arm suspension and transmits the drive force through the suspension. (Fig. 20) However, this design

Fig. 20, Wheel Robot 2005, the build version and the CAD model



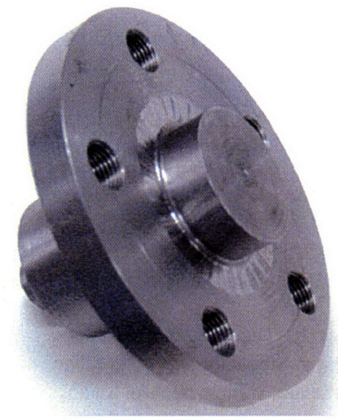


Fig. 21, Wheel Robot 2, custom made hub

iteration is not hubless. At the center of the wheel, a hub sits on two tapered roller bearings. (Fig. 21)

The wheel robot can be roughly divided into two halfs: the stationary part and the swing arm part. The stationary half faces the vehicle and holds the electric motor, the steering and leaning bearing, the connection to the seat, the fluidic muscle attachment points and the rear arm. The second half of the wheel robot is almost entirely dedicated to the swing arm which increases the challenge of also integrating the wheel bearing, drive train and brake in the remaining space. (Fig. 22)

The stationary side of the wheel robot is constrained by the

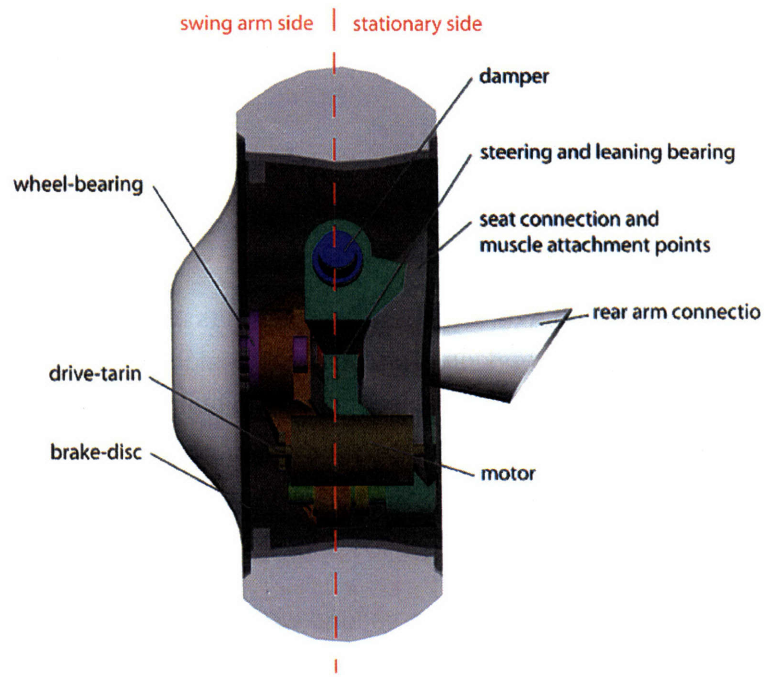


Fig. 22, Wheel Robot 2, Top View with labled Components

design-related connection points to the seat, fluidic muscles and rear arm. The latter must be mounted as far away from each other as possible to achieve the maximum muscle force without colliding with the suspension and the rear arm motion envelope.

The center cone of the supporting rear arm connects to the center steering and leaning bearing and requires a large motion envelope. This bearing is effectively a universal joint because it allows for movement in two axes rather than a spherical joint. (Fig. 23) The supporting rear arm is bolted to the universal joint in order to be detachable for transportation.

Fig. 23, Wheel Robot 2, Universal joint for steeing and leaning

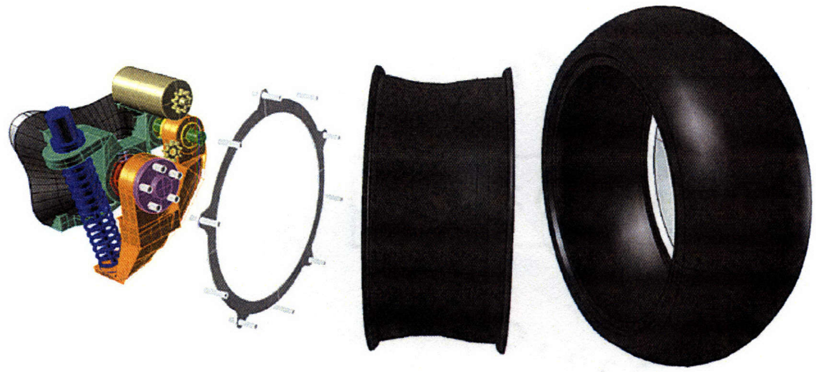


Fig. 24, Wheel Robot 2, tire, rim, brake disc, wheel robot explosion

Discussion

The motor is mounted close to the suspension axle on the sprung side of the wheel robot and reaches into the swing arm side to drive the suspension axle using a chain. A second chain mounted between the swing arm axle and the hub drives the wheel. This design includes a brake disc and caliper (Fig. 24). The brake disc is mounted between the rim and the spoke-plate of the two piece rim. The advantage of this outside brake

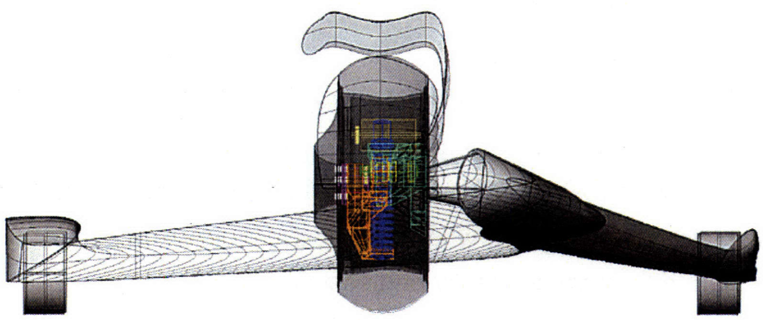


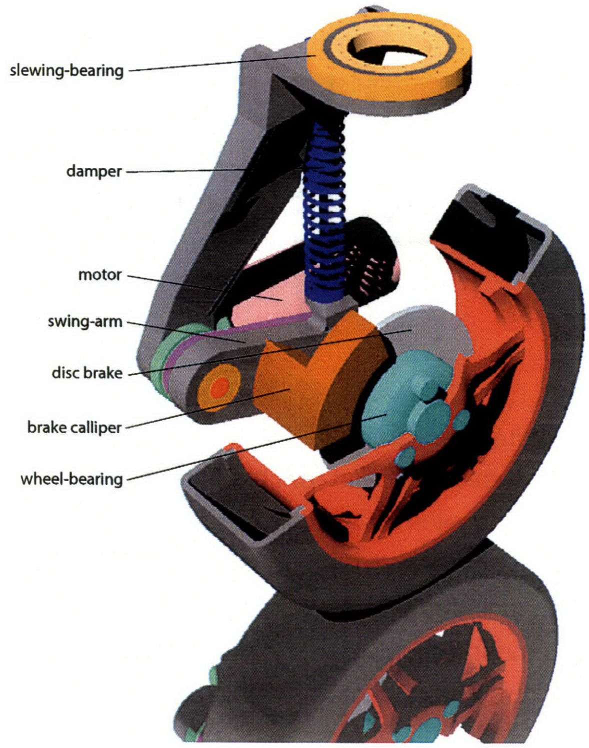
Fig. 25, Wheel Robot 2 and vehicle, front view

disc connection is the free space at the center of the wheel on the swing arm side where the drive chain and the wheel bearing have to be placed. The brake caliper is located as close to the suspension axle as possible in order to decrease its effect on the unsprung mass.

The whole wheel robot assembly including the rim and the spoke-plate are made of carbon-fiber reinforced composites. The molds for laying up the composites are also by Axel Kilian and Peter Schmitt. (Fig. 26) These composites were selected because they reflect a more realistic, light-weight material for a robot wheel. They also make it possible to build the forms envisioned for the athlete.

Fig. 26, Wheel Robot 2, carbon fiber rim during demolding

Fig. 27, Wheel Robot 3 with labeled components



Wheel Robot 3: Caster Iteration

The third wheel robot design iteration is unbuilt (Fig. 27). Omni-directional motion is the key phrase for a design exploration of a vehicle type using four wheel robots which are able to spin more than 360 degrees, ideally endlessly around the steering axle. The Smart Cities Group investigated this vehicle as the ultimate “freedom of motion” concept. Driving down the road this vehicle would allow turns around its own axle although this freedom would not necessarily be compatible with current driving conditions.

In order to achieve omni-directional steering motion, the wheel robot needs to be connected to the vehicle frame through the top, like a caster, rather than from the side as in a typical vehicle configuration. The top connection can be made in the most space efficient way as shown in the design with an over-sized slewing bearing capable of withstanding enormous lateral forces. (Fig. 27) The distance between the tire and the slewing bearing is constrained by the suspension travel clearance. I adapted the swing arm suspension solution to this particular design.

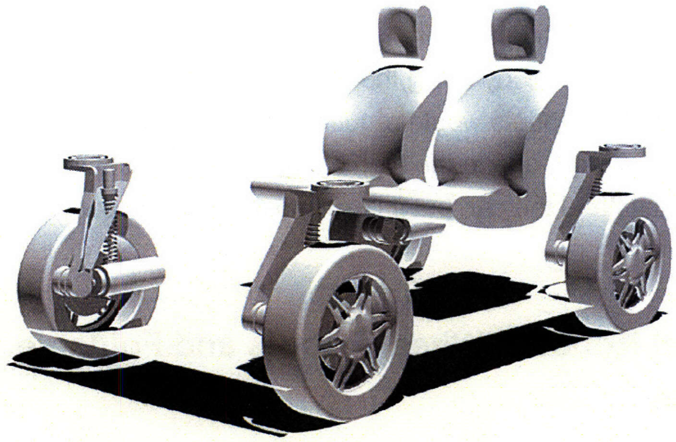


Fig. 28, Wheel Robot 3 vehicle configuration

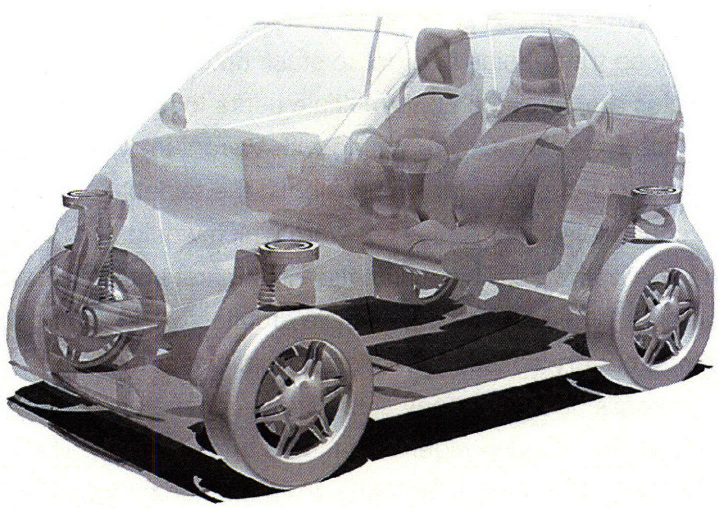
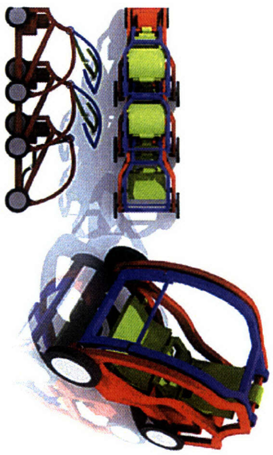


Fig. 29, Wheel Robot 3, proportion and motion envelope studgy

Discussion

As mentioned above, not all components of a wheel robot need to be fitted within the space of the rim as long as they stay within space reserved for the wheel to turn. This design iteration shows how this design principle could be implemented. Unlike the previous design iterations I use the void space provided by the vehicle body as the motion envelope of the wheel robot. The omni-directional wheel robot could house a conventional oil piston, coil spring suspension next to the wheel as well as the electric motor. A conventional hub mounted disc brake and caliper also fit inside the rim. Finally, the electronic components can also be housed in the space of the wheel robot.

The enormous height of this wheel robot design requires a much greater motion envelope than traditional wheels. The exercise shown in the adjacent figure (Fig. 28, 29) explores the possibilities of fitting four omni-directional wheel robots within a conventional car body using the Smart Car as a reference. These types of wheel robots would require a different configuration of car body frame work due to the high connection point between the wheel units and the car, but it is still possible within conventional proportions.



Wheel Robot 4: Wheel Robots and Foldable Frame

The stackable sharable city car by Franco Vairani (Fig. 30) drives the fourth wheel robot design iteration in combination with a holistic vehicle architecture. Vairani's design proposes a city vehicle whose frame folds in order to stack up like shopping carts. The vehicles are shared among multiple users to form a public transportation system. Collaborating with Vairani my work focuses on the design of the modular wheel robots, the foldable chassis and the control electronics plus software which would allow for the vehicle to be operated. This application is the first implementation that demands a comprehensive vehicle architecture including the connectors, battery boxes, control electronic and software.

Fig. 30, The Stackable Sharable City Car left: William Lark Jr. middle and right: Bit Car by Franco Vairani

Vairani's design already sets certain constraints. Safety reasons require the passenger cabin to be one rigid part. The folding chassis lifts and tilts the cabin from the horizontal into the vertical position. Vairani's design draws from the fact that vehicles are longer than they are high. He optimizes this relation to aciheve a folded footprint of 50% of the unfolded footprint. In order not to lift up the battery boxes which represent a huge part of the vehicle weight they should remain in their position. Due to the huge volume of the batteries I mix structure and energy storage and split the battery into two packs which also serve as front and rear axles for the chassis. Theses axles have the wheel robot connectors on the side so they can directly connect (Fig. 31) In order to maintain maneuverability it is important to remain the axle's position vertically throughout the folding and in the

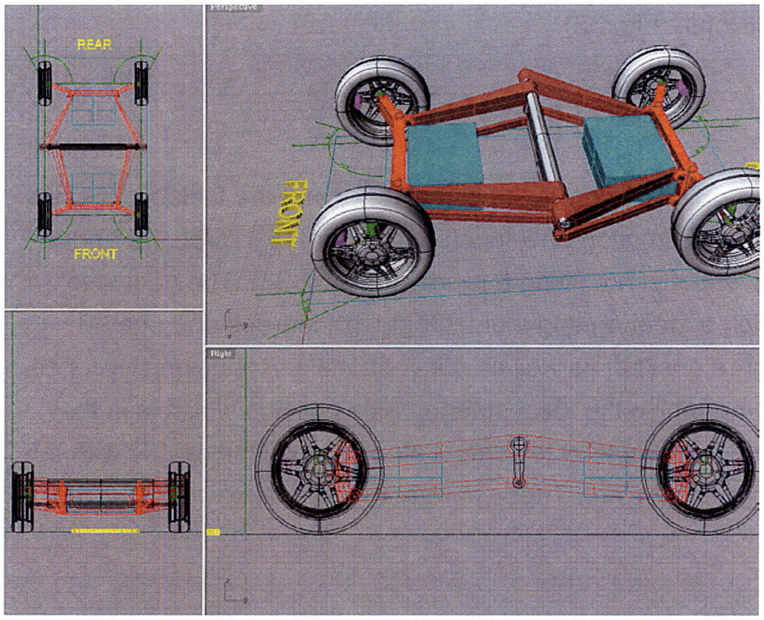
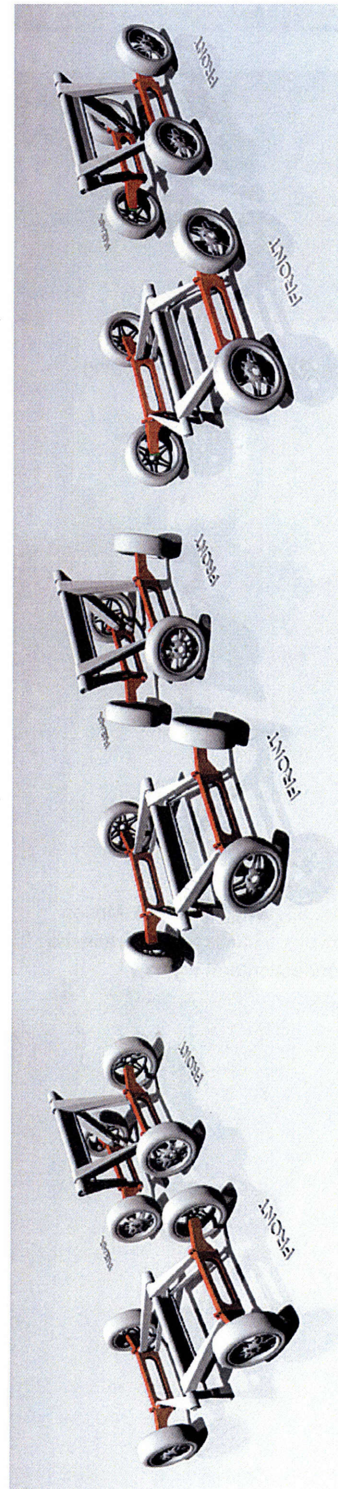


Fig. 31, The Foldable Frame
left: battery boxes, axles and folding mechanism
bottom: steering envelopes and folding positions



folded position. If the axles tilt the steering joint and the steering axle will tilt as well and steering in the folded position will become impossible (Fig. 31) A parallel shifting mechanism similar to the one in desk lamps links both axles and the folding joint between them and maintains the same angle of all three components throughout all positions. Ideally the folding is performed by the wheels rather than a dedicated actuator. The front wheels need to be locked by the brakes and the rear wheels push towards the front to lift the vehicle into its parking position.

Half-scale Vehicle Iteration 1

The ultimate goal is to prototype Vairani's design as a fully functional show car which requires designing and engineering all components at full scale. Unfortunately, the MIT Media Lab does not allow for vehicle prototyping at this scale. Because each step down in scale compromises part design the following studies are built at half-scale. To maintain the most compatibility with the full scale version I restrict the half-scale design to the components which can be scaled up to full scale or have a full scale equivalent. I also use the laser cutter and 1/8" plywood as the main prototyping material out of which bigger solid parts could be laminated. This prototyping process is fast and supports an iterative process which enables a rapid exchange between CAD

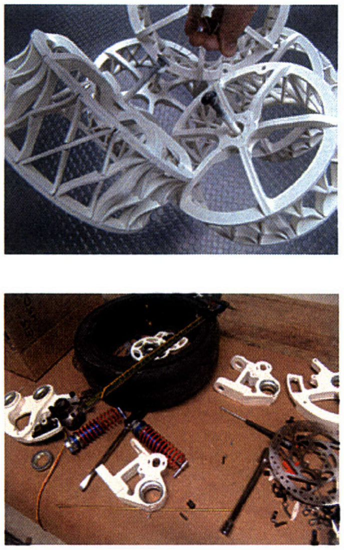


Fig. 32, Plywood Prototyping

design and physical mechanisms to highlight any constraints and collisions. (Fig. 32)

Foldable Chassis

The design of the wheel robot and the foldable chassis starts with motion envelope studies of a 15/175/55 tire and a conventional rim fitting this tire size (Fig. 33). The goal is to match a steering angle of left/right 30 degrees and one 90 degree position as well as conventional suspension clearance. I compromise the ideal steering axle position which is in the center of the wheel towards a steering axle that aligns with the outside of the rim. These parameters create a window in the

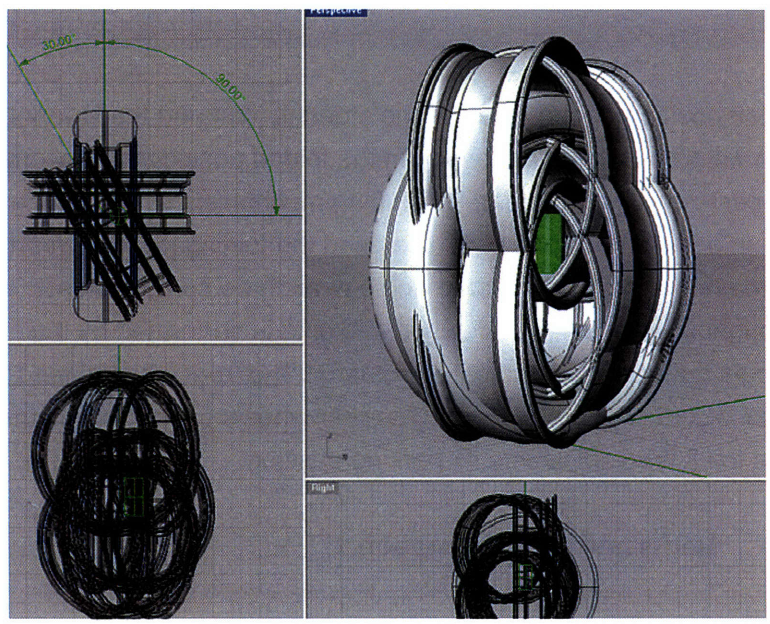
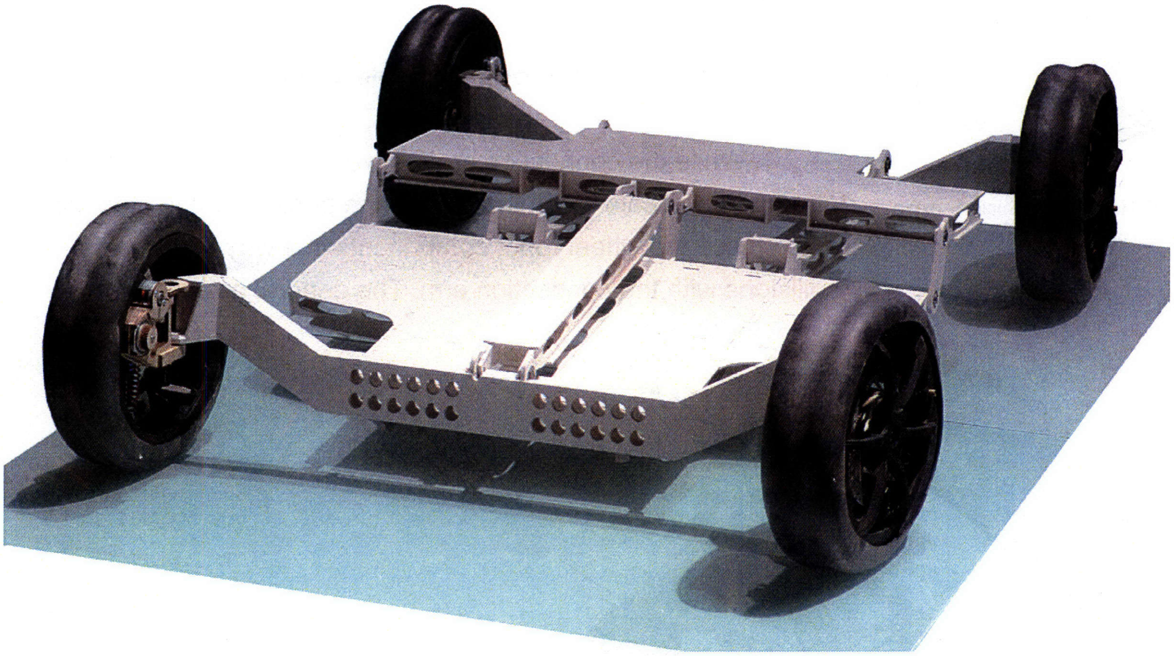


Fig. 33, Wheel Robot 3, Motion envelope studies to determin the connection arm window

motion envelope which guarantees a collision-free and structural connection to the vehicle. This window also determines the angle and minimum length of the vehicle connection arm. The axles are just a straight connection between the left and right wheel robot connection arm and provide the rotation points for the folding mechanism. The holes in the axles each fit one battery cell to create the battery pack. The basic proportions of the folding mechanism are given by the passenger cabin and its rotation and support points. The height of the folding mechanism is related to



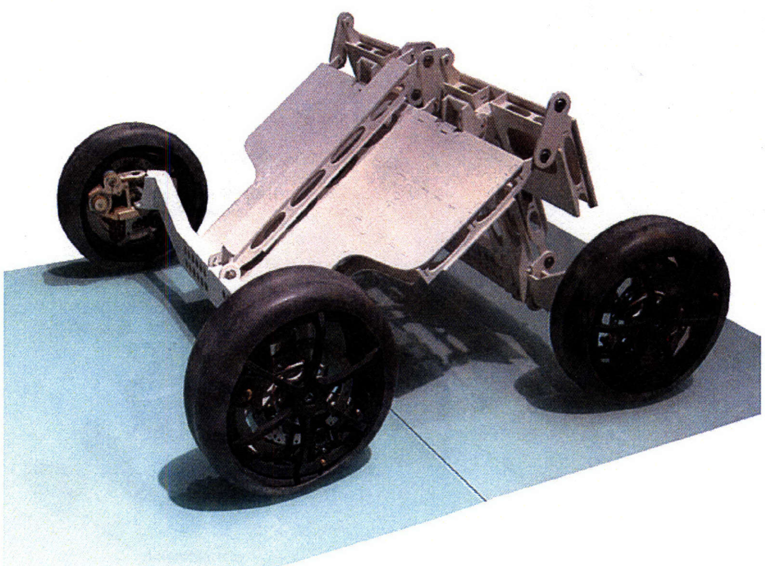


Fig. 34, Half Scale Vehicle 1
above: unfolded
left: folded

the clearance between the upper and lower layer which shrinks during folding. I settle on a proportion in which the upper and lower layer actually tough in the most upright position and by this represent a hard stop for this motion. The front upper layer of the folding mechanism has to be restricted to a small middle bar in order to allow the necessary foot room for the passengers (Fig. 34). I also create a CAD model of the half-scale cabin after Vairanis design by rebuilding the geometry only using single

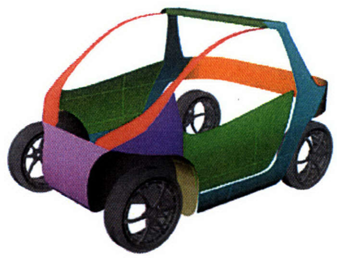


Fig. 35, Half scale Vehicle 1, explorable surfaces cabin model

curved surfaces in order to prototype the cabin using flat sheet materials.

A Wheel Robot for a Foldable Vehicle Architecture

While the connection arm between wheel robot and vehicle already represents a compromise of the position of the steering axle I place the wheel robot components in a way that avoids collisions with the connection arm. The general arrangement of

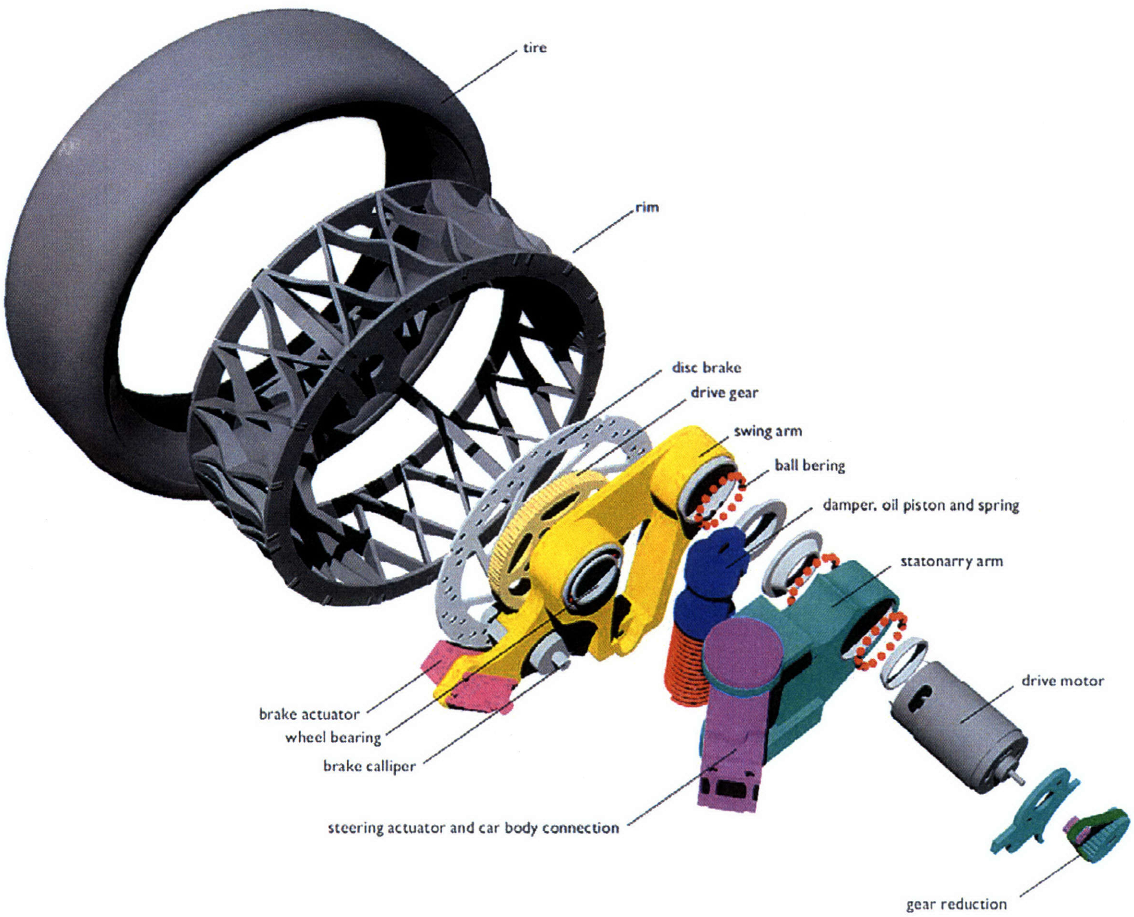


Fig. 36, Wheel Robot 4 with labeled components

components resembles the wheel robot for the one wheel athlete.

Again the space inside the wheel can be split into two halves: the swing arm and the stationary part. The swing arm houses the hub, the disc brake caliper and its actuator. The wheel and tire connect to the swing arm (Fig. 36, 39). The wheel and tire are a half-scale version of the actual rim and tire and consist of two bicycle inner tubes which represent the air filled tire and a plywood constructed rim. The disc brake connects to this rim. The swing arm is connected to the stationary arm through the suspension swing axle which is again used to transmit the drive force. In this design, I use plywood belt bully gears to transmit the drive force.

The damper sits between the swing arm and the stationary part of the wheel robot. It is a quarter scale model truck oil piston and coil spring damper which functions in the same manner as a conventional car damper. Ironically, a quarter scale model of a truck damper fits a half-scale model of a wheel robot. The difference in scale has no effect on the suspension travel because the damper is placed in the middle of the swing arm between the suspension swing axle and the hub where it travels half of the way the wheel travels.

The stationary part of the wheel robot houses the motor, the steering bearing, the steering actuator and the drive electronics. The case of the steering actuator slides exactly into the connection arm to the chassis and represents the mechanical link between wheel robot and chassis. The electrical connection will be established using plugs.

The Desing allows for steering from 30 degrees one side to 90 degrees opposit side (Fig. 38). The suspension travel clerance is comparable to normal vehicle and as shown in (Fig. 37) the redish part stays stable while the rest moves up and down for suspension.

Fig. 37, Wheel Robot 4, Suspensi- on Diagram

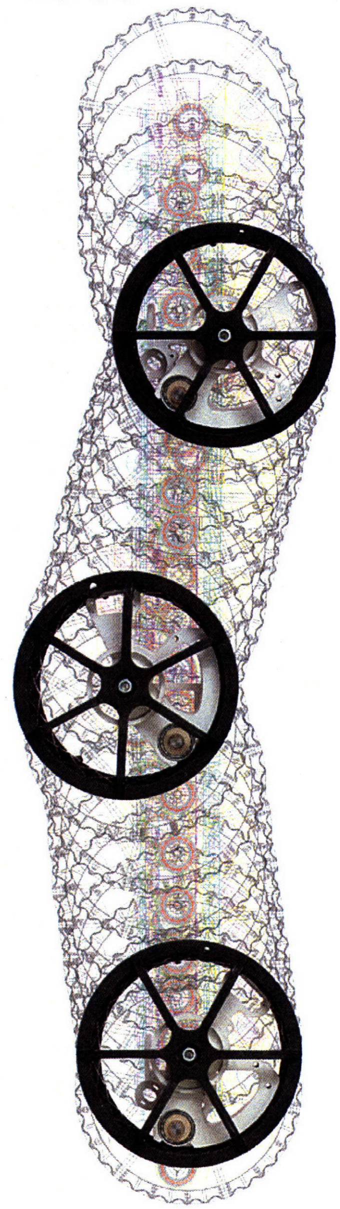


Fig. 38, Wheel Robot 4, Stee- ring Motion Diagram

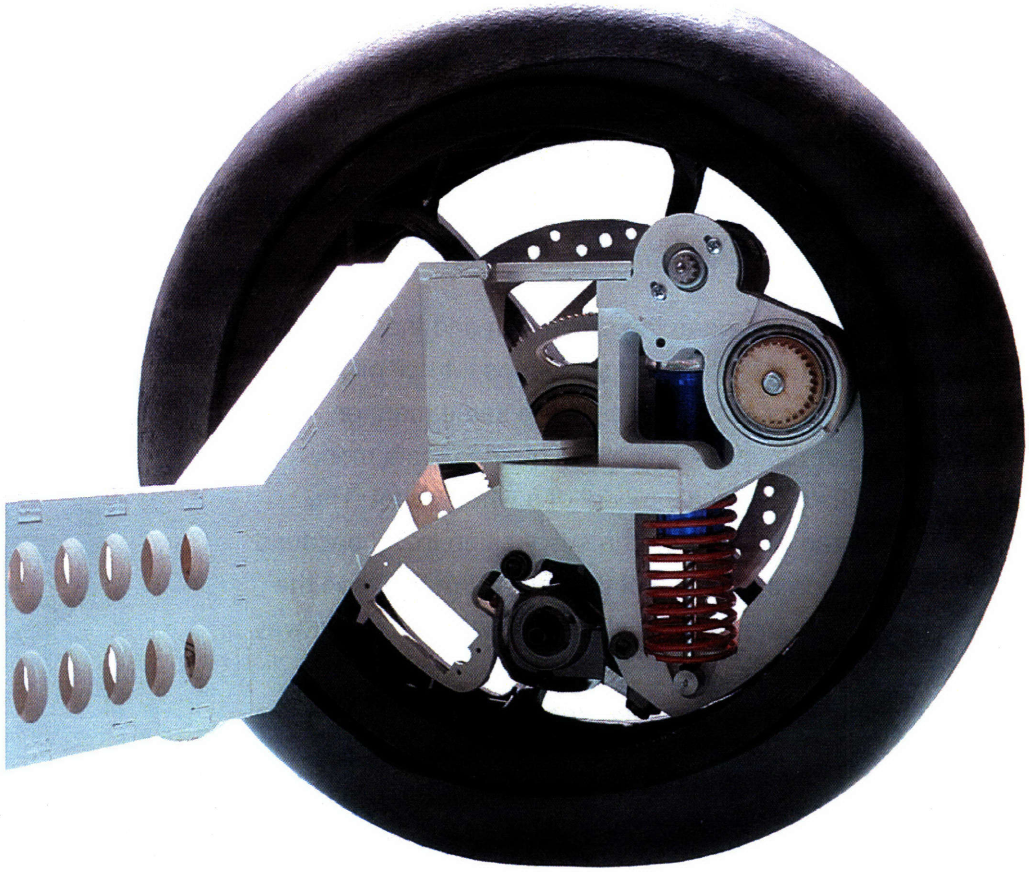


Fig. 39, Wheel Robot 4 prototyped in Plywood

Discussion

The first half-scale vehicle model revealed many important findings that will guide the design development of the half-scale vehicle described in chapter 3. The parallel shifting mechanism does not solve the folding problem because it only maintains the angles between the axles, but it does not stabilize the axles in their upright position. As a result, the mechanism is dependent on a dedicated actuator which would stabilize and actuate the mechanism. The next iteration, therefore, must address this problem.

The prototyping process should try to use as many realistic materials as possible. Though plywood has the benefit of rapid design iterations it does not appropriately reflect the functionality and accuracy a mechanical assembly requires.

The connectors between the robots and the chassis need more development. Future designs should better integrate the structural and electrical connections between the chassis and the drive unit.

Chapter 3: Half-scale Vehicle Iteration 2

Revised Design Principles: Simplicity and Multifunctionality

The fifth wheel robot design iteration differs significantly from the previous ones. Two influences triggered a holistic redesign according to the principles of simplicity and multifunctionality: a workshop with Ferrari and the Printed Motors, Ltd. Mini Cooper Concept Car, PML for short (2006, Ref. 15). Discussions with engineers at Ferrari led to a new emphasis on simplicity and performance for the wheel robots. The PML is the first widely known concept vehicle with a simple, multifunctional in-wheel motor design.

In January 2007, I participated in a workshop with Ferrari engineers in Maranello, Italy. These automotive and race car specialists uncovered an unexpected connection between my wheel robot research work and their emphasis on efficiency in race car design. Efficiency for Ferrari engineers means reducing designs to their simplest form and using as few parts as possible, especially movable parts. Combining several functions in one component reduces weight, energy consumption, complexity, and manufacturing costs by decreasing the number of parts. Also fewer parts make the overall system less likely to fail and thus more reliable. The same considerations can be used to redesign the stackable sharable city car and its key component, the wheel robot.

To date, only one concept vehicle successfully demonstrates the type of simplicity and multi-functionality which I have identified as design principles for wheel robots: the Mini Cooper modified by PML (2006, Ref. 17). This vehicle showcases the capabilities of PML's electric in-wheel motors and their multifunctionality. Not only do the in-wheel motors accelerate and decelerate the vehicle, they also brake. In other words, the PML has no dedicated braking system because the in-wheel motors are powerful enough to perform the functions of a traditional brake system.

Although the PML uses one-of-a-kind, hand-made electric motors the specifications of the series in-wheel motors prove the feasibility of designing a safe vehicle without brakes. PML's in-wheel motors allow for up to 640 Nm of stall torque (30 sec max) which can be used for acceleration or deceleration. Also, each in-wheel motor weighs only 18 Kg despite its oversized, conventional five-bolt wheel bearing (Ref.16). The weight is comparable to a conventional wheel bearing disc brake assembly which means the unsprung or rotational mass is not increased by the in-wheel motors. Thus the PML fulfills three roles in the electric vehicle acceleration, deceleration and power generation through regenerative braking. And most importantly the design accomplishes these goals without increasing the unsprung mass of the wheel assembly.

Wheel Robot 5 and the Half-scale Vehicle Iteration 2

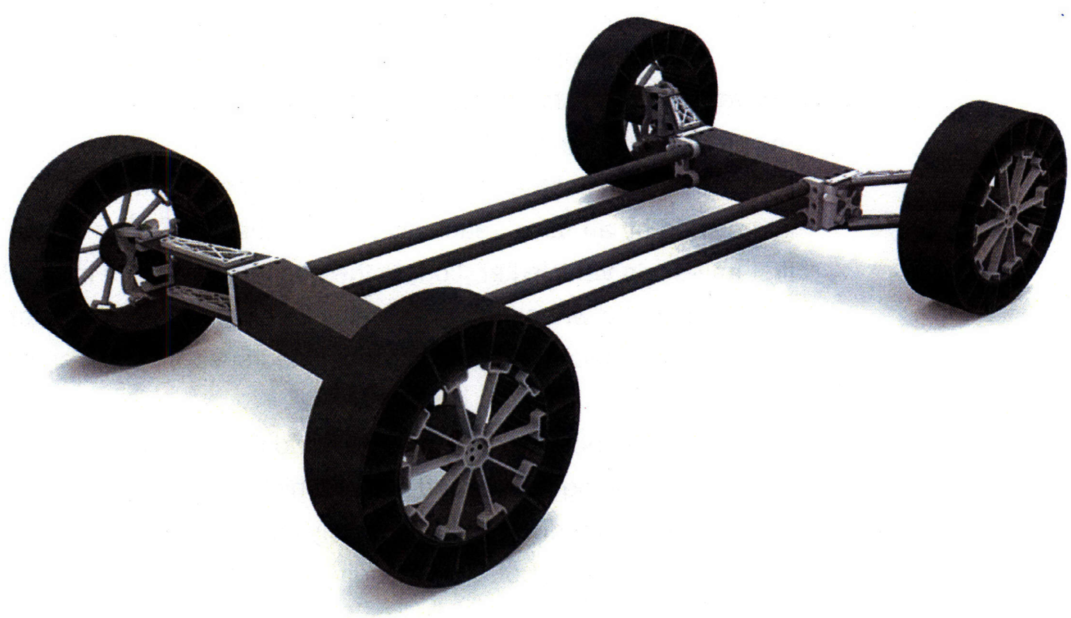


Fig. 40, Half Scale Vehicle 2

The second iteration of the half-scale vehicle essentially consists of a front and rear axle, which house the batteries and end with four connector bolts on each side (Fig. 40). Vairani's latest design of the folding mechanism includes sliding rails in the vehicle cabin. For the purpose of the second version of the half-scale vehicle simple spacer rods have been placed between the axles. This platform serves as a test-bed for a new wheel robot iteration that implements the design principles of multifunctionality and simplicity.

Wheel Robot 5

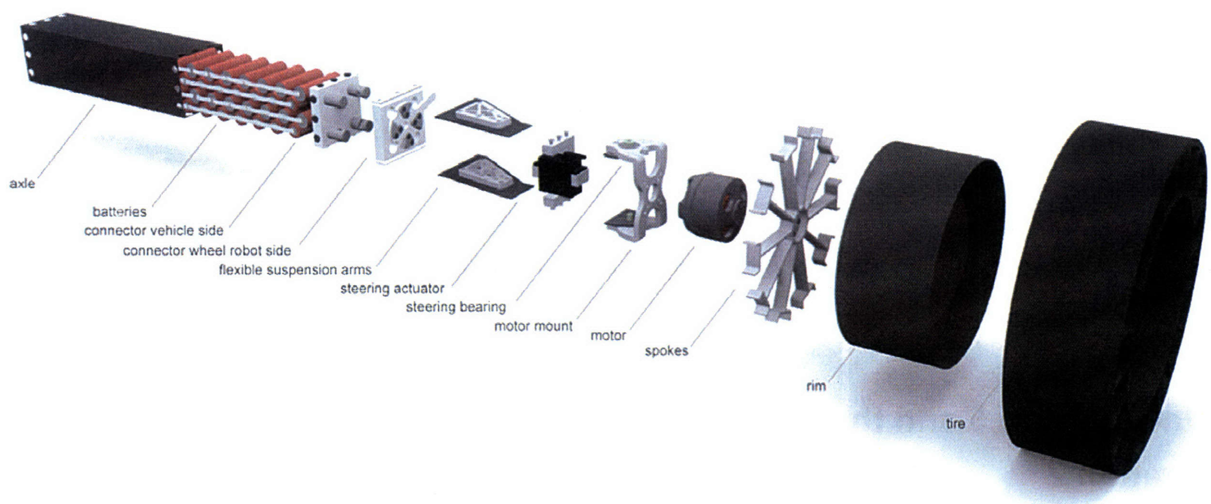


Fig. 41, Wheel Robot 5 with labeled components

The position of the connector between the wheel robot and the vehicle is the starting point for the fifth wheel robot iteration. In my previous designs, the connector does not extend far beyond the wheel robot. Instead the space for the wheel motion envelope is provided by an "arm" reaching out from the chassis as in the first half-scale vehicle iteration. In the second iteration, I integrate the arm into the wheel robot assembly by placing the connector more evenly spaced between a redesigned suspension arm and the vehicle.

The suspension arm in the second iteration is inspired by the PML technology described above which demonstrates that an in-wheel motor does not necessarily increase the unsprung mass in the wheel robot. This fact gives the designer more freedom to rethink the working principle of the suspension as it will not have to compensate for additional mass. Inspired by the Ferrari formula one race car double wishbone suspension I use the connection arm itself as a suspension component instead of a complex in-wheel suspension (Fig. 41, 42). In addition, the

Cannonadale scalpel carbon flexure rear suspension bike frame (Ref. 1) shows how mechanical joints to pivot the suspension arms can be eliminated. A simple carbon-reinforced composite material allows for the necessary flexing of the suspension. This composite part is reinforced by aluminum plates to restrict the flex

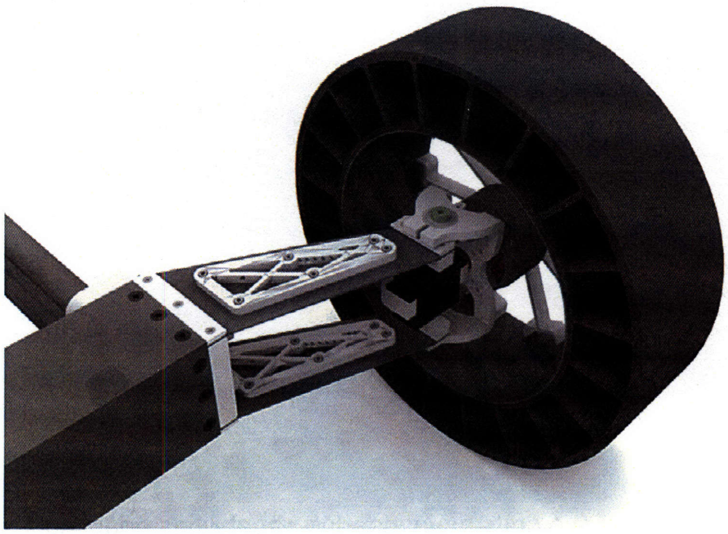


Fig. 42, Wheel Robot 5 assembled

to the desired areas.

The modified suspension arm design makes it possible to place the connector at the border line between wheel motion envelope and vehicle (Fig. 43). This position is much more beneficial than the previous positions closer to the wheel because it allows for a significant simplification of the wheel robot design and assembly.

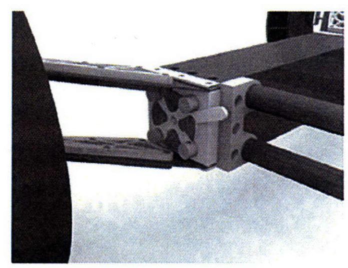


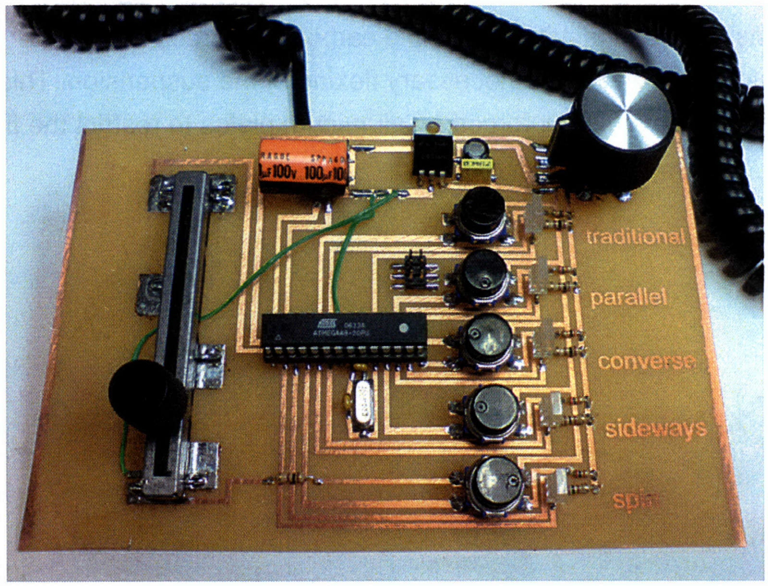
Fig. 43, Wheel Robot 5, the Connector

This basic configuration of connector and suspension arm also determines the position of the steering bearing, actuator and the motor. The steering components are placed at the other end of the suspension arm and connect directly to the motor which is also the hub of the wheel.

The electric motor in the half-scale design resembles PML's motor technology, but its braking capability is not as outstanding. It is a model aircraft permanent magnet, 3-phase, brushless outrunner motor with 12 poles. The spokes of the rim connect from the motor to the rim cylinder where a run flat tire is mounted. Together this wheel robot iteration achieves a much simpler design using fewer parts in a less complex configuration.

Electronics and Drive-Modes

Fig. 44, Driver Input Device, Throttle and Steering Controll, Drive Mode Selection



All four drive units have steering capabilities enabling several drive-modes for the vehicle. In the current design, the driver can select among five different drive-modes. The **traditional** drive-mode limits the vehicle to front wheel steering only. The **parallel** drive-mode rotates all four wheels simultaneously which allows for parallel line shifting. This mode does actually not cause the vehicle to perform any curved motion. In the **converse** drive-mode all four wheels are steered conversely towards each other. If the front wheels steer right the rear wheels steer left and by this the turning radius is decreased tremendously compared to traditional front wheel steering. The **sideways** drive-mode is similar to the parallel drive-mode only the wheels are frozen to the 90-degrees position to allow for sideway motion. In this mode, the driver steering input is deactivated. The sideway drive-mode is very useful for parking in tight spots. The **spin** drive-mode is similar to the converse drive-mode only that the wheels are frozen to a specific angle given the vehicle's width and length which allows it to spin on the spot. Again the driver steering input is disabled. This drive-mode can be used for 180-degree turns and makes driving in reverse superfluous. My driver input device makes it possible to switch between different drive modes by pressing the mode selection button and provides a throttle control potentiometer as well as a steering control potentiometer. (Fig. 44)

The drive electronics architecture consists of four wheel robot microcontrollers (Fig. 45) participating as slaves in a two wire interface (TWI) bus and the driver input device (Fig. 44) participating as the master on the TWI bus. The wheel robot microcontrollers each interface with the motor drive electronic and the steering device. The driver input device reads in the potentiometer values and converts them. The two converted values and the drive-mode status is continuously transmitted via the TWI bus and the wheel robot microcontroller update their data registers accordingly (Fig. 46).

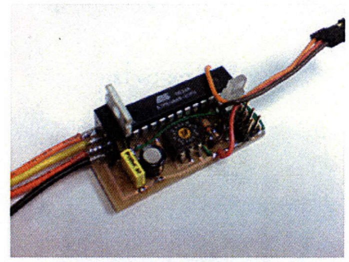


Fig. 45, Wheel Robot Microcontroller

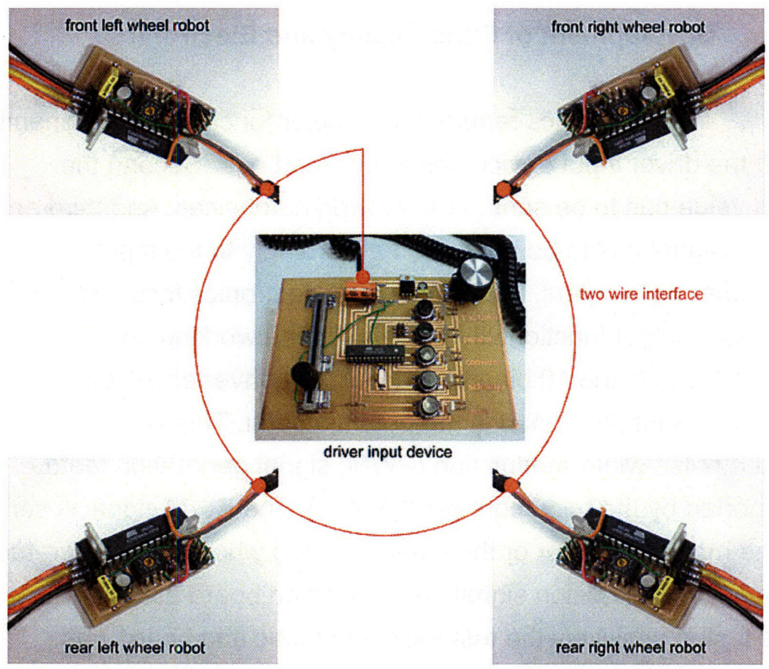
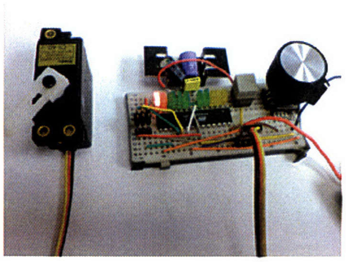
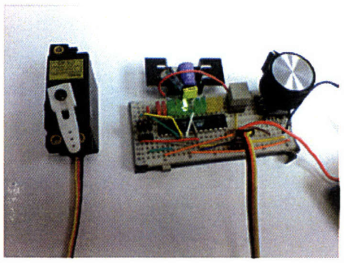


Fig. 46, Drive Electronic Architecture Diagram

The networked microcontroller approach has several advantages over a PC or similar high-level device. First, scalability is an important factor. State of the art vehicles use a controller area network (CAN) bus to interface between different participants like motor, brakes, doors, etc. For demonstration purposes, it is very useful to create a comparable system in which the wheels are active participants rather than passive instruction receivers. This approach is comparable to state of the art vehicle technology and can be scaled up to vehicles just by switching bus protocols.





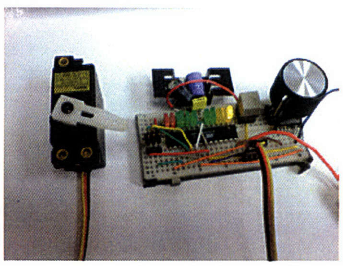
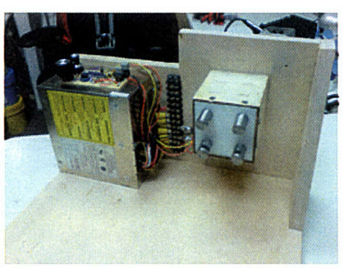
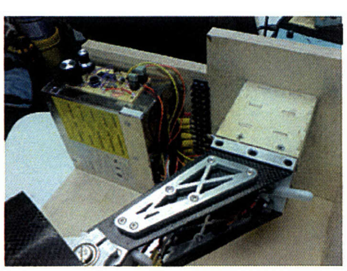


Fig. 47, above:Input Output Development using Analog to Digital Converter to create Pulse With Modulationn Signals
below: Test Rick Assembly operating one Wheel Robot





Second, separation of tasks within the network increases overall performance. The networked microcontroller approach grants the wheel robots some autonomy. They become semi-autonomous elements that govern their own functionality and compute the associated parameters on board. As a result, the wheels develop into a subsystem with independent capacities. The vehicle CPU or computer can then focus on other tasks. Third, augmenting the wheels with their own computational capacity increases the refresh rate of feedback loop and sensor readings and output cycles as compared to one computer taking care of all four wheels. Fourth, stability of operation increases with an increasing number of controllers and subsystems. Finally, I should note that microcontrollers are significantly cheaper than any other solution.

Development of Functionality and Electronics

The electronics require three major functional components. First the driver input device has to be “read out”. Second the read value has to be sent to the networked devices. And third an output signal has to be generated accordingly to the input data and other parameters. I developed the electronics focusing on the input-output functionality first and the networking second. (Fig. 47) Using the 10 bit analog to digital converter (ADC) on the microcontroller I read in the potentiometer. This value serves for the pulse-width-modulation (PWM) signal generation feature supported by the microcontroller (Ref. 2). The PWM signal is send to the motor controller or the steering servo where it is interpreted as a speed or position signal. After a bread board assembly was tested positively the test Rick schematic and board was prototyped. (Fig. 47) The test rig operates a single wheel robot and proofed the concept as feasible. After this basic functionality was proven I developed the actual wheel robot microcontroller unit and the driver input device implementing the TWI bus.

Software and Computation

Despite the advantages of a high refresh rate, stable operation and low cost of microcontroller-based control electronics, there are some computational challenges that can be overcome. Unfortunately, the real-time processing power of a microcontroller CPUs is not capable of calculating a large number of parameters out of a broad geometry continuously. Computing the ideal outputs from the basic vehicle dimensions, wheel robot positions (front right, etc.) and driver input data would not be possible with the processor on-board the selected microcontroller. Therefore, my driver interface software executes the formulas derived from a geometrical approximation of the specific wheel robot behavior.

The five drive-modes can be separated into two scenarios which require individual real-time computation: the traditional front wheel steering and all four wheel converse steering. The sideways drive-mode does not require any specific wheel robot computation because all wheels rotate to the 90-degree position and drive at the same, driver input speed. In the all four wheel parallel drive-mode the vehicle actually does not perform any curved motion. In other words, the same driver input angle and speed can be applied to all four wheels. The spin on spot case is a fairly easy situation in which the vehicle spins around its center point. The wheel robots are required to move to a fixed angle position which is directly related to the vehicle with and length. (Fig. 48) At this angle the wheels are tangential to the circle around the vehicle center trough the center points of all four wheels.

Using CAD software and a simplified drawing of the half-scale vehicle in top view, I determined the angle of 55.16 degrees for the half-scale vehicle dimensions of 758mm with and 1250mm length (Fig. 48). Instead of recalculating this value in real time, this angle value will be stored as a variable in the wheel robot microcontroller and can be accessed at any time when the spin on spot drive-mode is activated by the driver through the interface device. The procedure for determining the angles and turning radii is the same for the other two driving scenarios. Because the wheel robots are restricted to +/- 30 degrees of steering and 100% of speed the driver input data has to be mapped to the wheel robots in a way that assures no wheel robot extends the max values in any possible driving scenario. For example the steering input data is mapped to the curve inner wheel because it needs to rotate more than the curve outer wheel while the speed input is mapped to the curve outer wheel because it travels

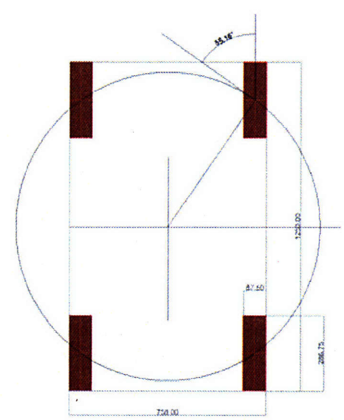


Fig. 48, Spin Mode angle determination diagram

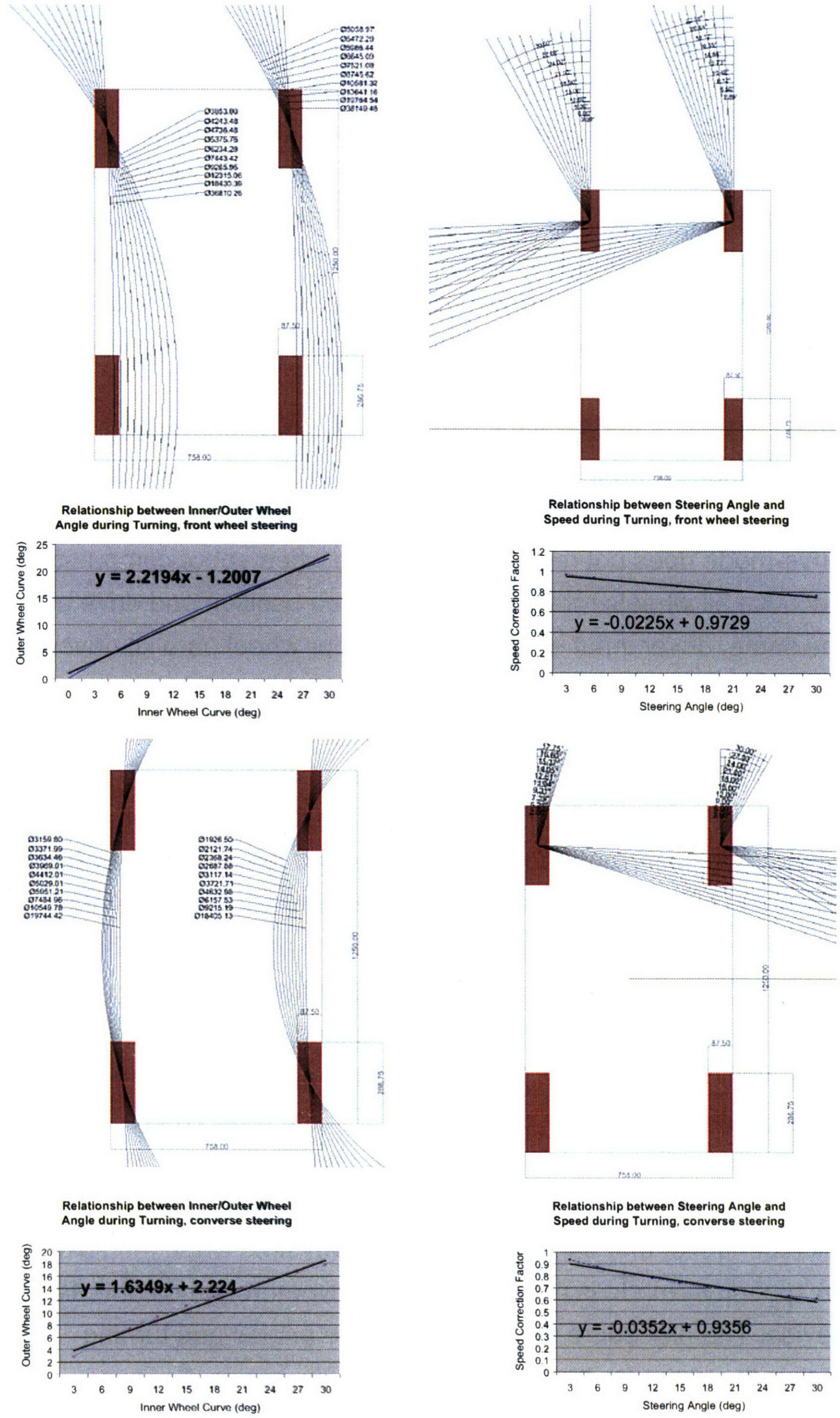


Fig. 49, Geometrical Approximation Approach to determin dependency formulars

on a bigger circle and needs to spin faster. This assures the wheel robots only subtract specific factors from the input data rather than adding. For a sample set of 10 different input cases I geometrically determine the resulting corrections for the other wheels (Fig. 49). The steering angle also describes the turning circle of the vehicle which influences the individual speed of the wheels. So in addition to the steering angles I also generated the turning circle diameters. For the scenario of traditional front wheel steering I approximate the formula y = 2.2194x - 1.2007 for the steering angle corrections and y = -0.0225x + 0.9729 for the speed value corrections. Accordingly for the scenario of the four wheel converse steering I approximate the formulas y = 1.6349x + 2.224 for the steering angle corrections and y = -0.0352x + 0.9356 for the speed value corrections. These formulas can now be implemented into the wheel robots software and need to be updated in case the wheel robots are connected to a vehicle with different dimensions.

The following excerpt shows how the findings are reflected in the source code for the example of the converse steering mode:

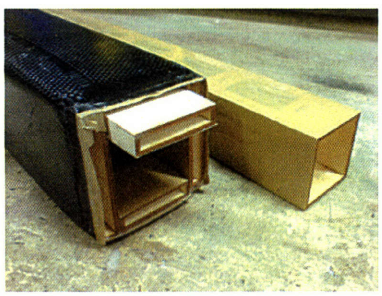
line 184, 203, 223: speed value correction
line 190, 209: angle value correction
line 220: angle value invertation due to converse mode rear wheel steering

```
176  if (mode == 3) //converse
177      {
178      if (position == 1) // front right
179          {
180              if ( steering_value > 512) // curve inner wheel, direct match steering value and correct speed value
181                  {
182                  pwm_steering_duty_cycle = ((steering_value + 4608) / 6.83); // output calculation, limits steering to +/- 30 degree
183                  set_steering_duty_cycle ( pwm_steering_duty_cycle ); // call output function with calculated value
184                  speed_value = ((-0.0352 * speed_value) + 0.9356); // y = -0.0352x + 0.9356
185                  pwm_speed_duty_cycle = ((speed_value + 1536) / 3.41);// output calculation, limits motor power to 50%
186                  set_speed_duty_cycle ( pwm_speed_duty_cycle ); // call output function with calculated value
187                  }
188              if ( steering_value < 512) // curve outer wheel, correct steering value and direct match speed value
189                  {
190                  steering_value = ((1.6349 * steering_value) + 2.224); // y = 1.6349x + 2.224
191                  pwm_steering_duty_cycle = ((steering_value + 4608) / 6.83);// output calculation, limits steering to +/- 30 degree
192                  set_steering_duty_cycle ( pwm_steering_duty_cycle ); // call output function with calculated value
193                  pwm_speed_duty_cycle = ((speed_value + 1536) / 3.41);// output calculation, limits motor power to 50%
194                  set_speed_duty_cycle ( pwm_speed_duty_cycle ); // call output function with calculated value
195                  }
196          }
197      if (position == 2) // front left
198          {
199              if ( steering_value < 512) // curve inner wheel, direct match steering value and correct speed value
200                  {
201                  pwm_steering_duty_cycle = ((steering_value + 4608) / 6.83); // output calculation, limits steering to +/- 30 degree
202                  set_steering_duty_cycle ( pwm_steering_duty_cycle ); // call output function with calculated value
203                  speed_value = ((-0.0352 * speed_value) + 0.9356); // y = -0.0352x + 0.9356
204                  pwm_speed_duty_cycle = ((speed_value + 1536) / 3.41);// output calculation, limits motor power to 50%
205                  set_speed_duty_cycle ( pwm_speed_duty_cycle ); // call output function with calculated value
206                  }
207              if ( steering_value > 512) // curve outer wheel, correct steering value and direct match speed value
208                  {
209                  steering_value = ((1.6349 * steering_value) + 2.224); // y = 1.6349x + 2.224
210                  pwm_steering_duty_cycle = ((steering_value + 4608) / 6.83);// output calculation, limits steering to +/- 30 degree
211                  set_steering_duty_cycle ( pwm_steering_duty_cycle ); // call output function with calculated value
212                  pwm_speed_duty_cycle = ((speed_value + 1536) / 3.41);// output calculation, limits motor power to 50%
213                  set_speed_duty_cycle ( pwm_speed_duty_cycle ); // call output function with calculated value
214                  }
215          }
216      if (position == 3) // rear left
217          {
218              if ( steering_value < 512) // curve inner wheel, direct match inverted steering value and correct speed value
219                  {
220                  steering_value = (512 + (512 - steering_value)); // inverts steering value for rear position
221                  pwm_steering_duty_cycle = ((steering_value + 4608) / 6.83); // output calculation, limits steering to +/- 30 degree
222                  set_steering_duty_cycle ( pwm_steering_duty_cycle ); // call output function with calculated value
223                  speed_value = ((-0.0352 * speed_value) + 0.9356); // y = -0.0352x + 0.9356
224                  pwm_speed_duty_cycle = ((speed_value + 1536) / 3.41);// output calculation, limits motor power to 50%
225                  set_speed_duty_cycle ( pwm_speed_duty_cycle ); // call output function with calculated value
```

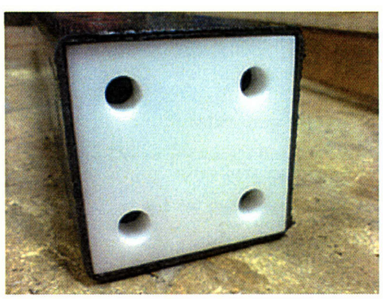
Just build it! Prototyping the Half-scale Vehicle Version 2

This section describes the prototyping process of the half-scale vehicle which includes all the mechanical, composite and electronic components. The series of images recreates the building process with an emphasis on the specific construction methods used in each phase (Ref 6).

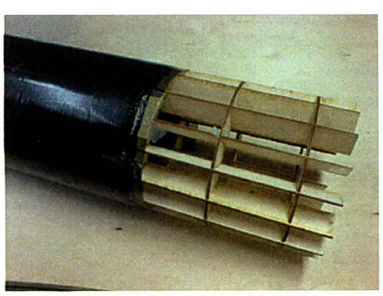
A square carbon fiber tube is molded around a five piece laser-cut plywood core.



The composite shrinks around the core during hardening. The core can be disassembled piece by piece.

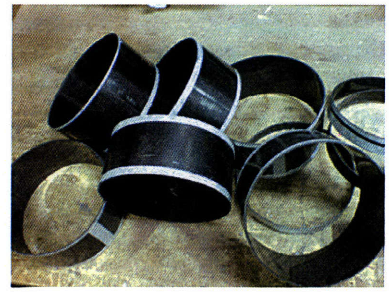


A waterjet cut Delrin side plate fits perfectly into the square carbon tube.

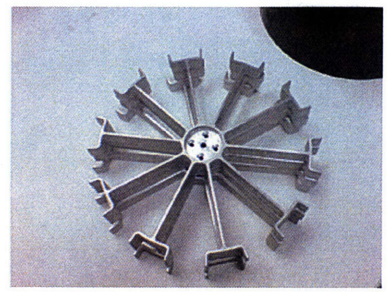


A round carbon tube is also molded around a laser-cut plywood core. The core can also be dissassembled for easy demolding under the composite's shrinkage pressure.

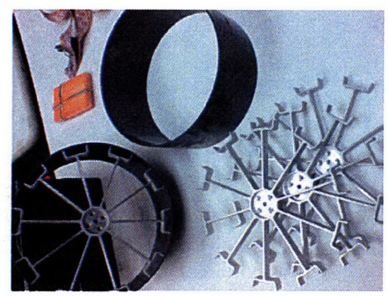
The round carbon tube is cut into the desired width for the rim pieces.



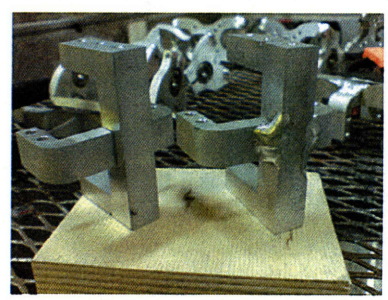
Wheel spokes are cut out of aluminum using the water jet cutter. The center piece connects to the motor and is friction fit into the wheel spokes component.



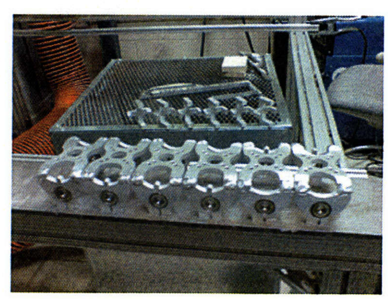
The spokes and the round carbon tube are assembled, friction fit and glued together for additional hold.

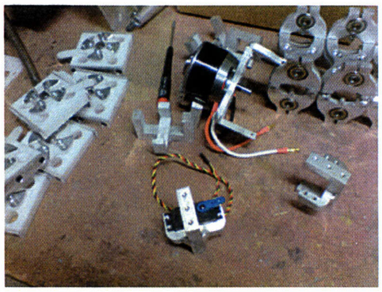


The water jet cut suspension arm end pieces are welded together using a TIG welder.

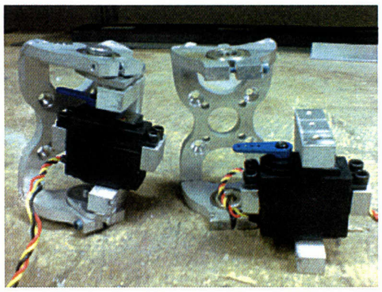


The water jet cut motor mount pieces are welded together as well and equipped with ball bearings for steering.



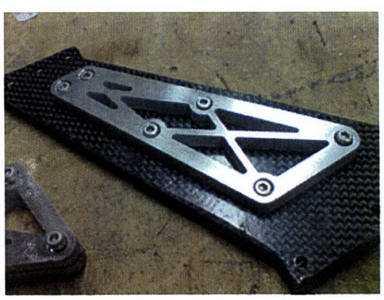


The motor and steering servo are connected to the motor mount and suspension arm end pieces.

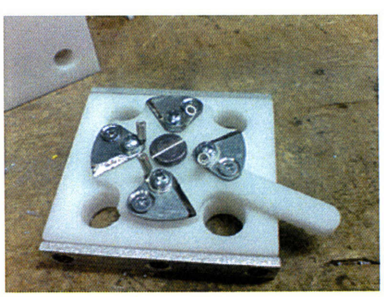


The suspension arm end piece assembly is connected with the motor mount.

Aluminum flexure reinforcement pieces are water jet cut and taped.



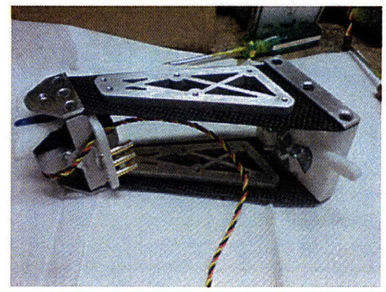
The suspension arm flexure pieces are assembled. The reinforcement pieces limit the flex to the outer edges.



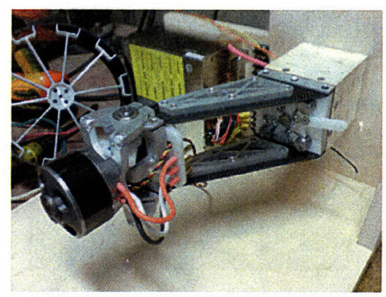
A Delrin connector plate for the wheel robot is water jet cut and assembled with the metal conductors and soldering sockets.

The suspension arm flexure pieces are assembled with the connector plate.

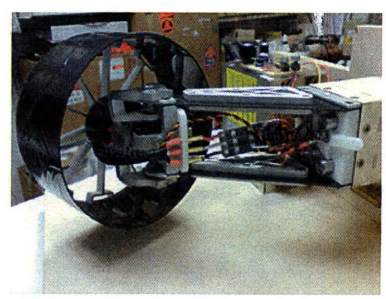
The suspension arm end piece assembly is connected to the suspension arm flexure piece.



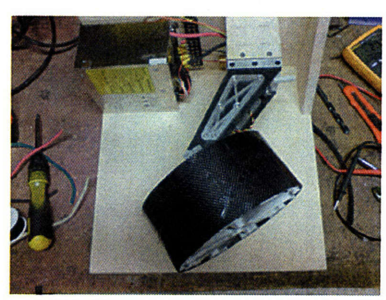
One wheel robot assembly is mounted to a test rig and the electric connectors are adjusted.

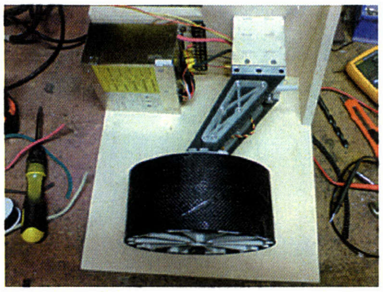


The wheels are mounted to the wheel robot assembly.

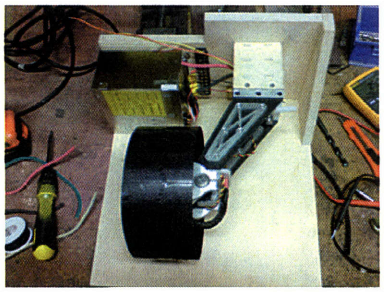


The steering angle of 30 degrees on one side is adjusted.



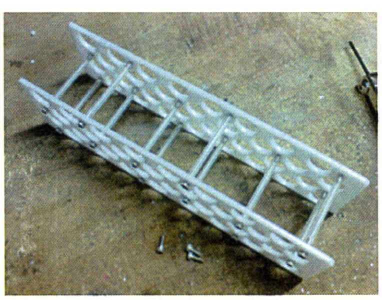


The steering angle zero position is adjusted.

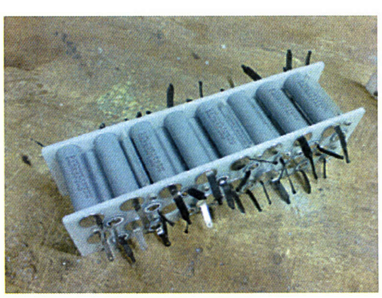


The steering angle of 90 degrees on the other side is adjusted.

Two battery holders are laser cut out of Delrin.

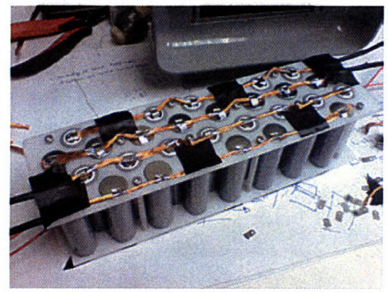


The battery holder body is assembled using spacers to keep the two sides at a distance.

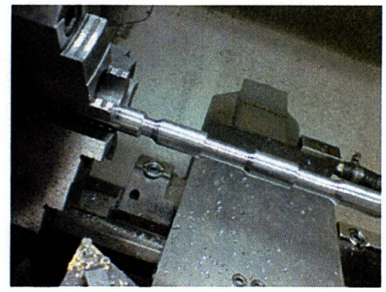


The batteries are fitted into the battery holder.

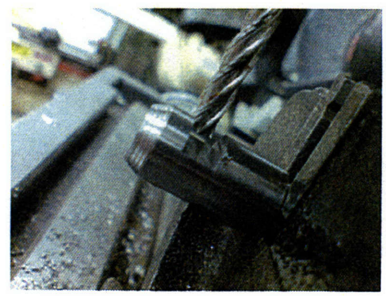
The wiring for the battery pack is completed using the soldering lips of the batteries. Now the battery holders can be slotted inside the front and rear axels.



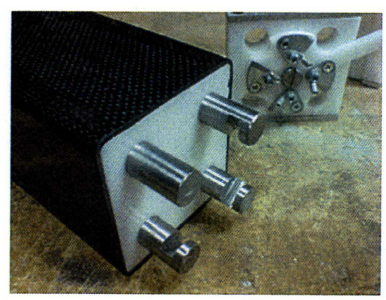
The connection rods between the vehicle and the wheel robot are lathed out of steel.



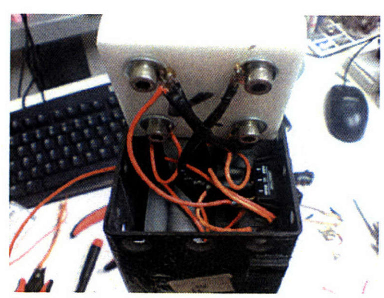
The bayonet mount grooves are milled into each connection rod.

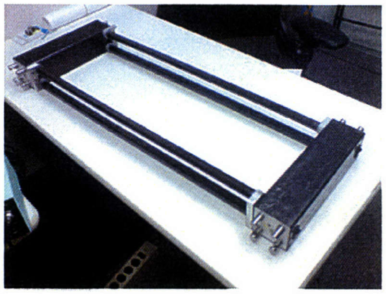


The vehicle side of the connector is assembled.

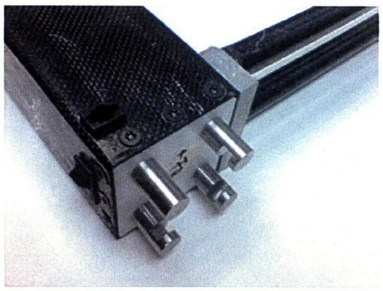


The batteries are wired to the connection rods.

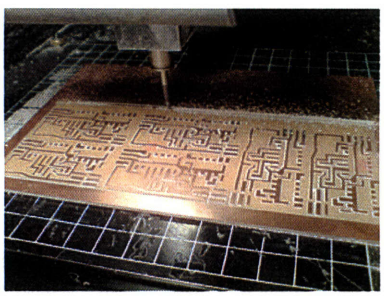




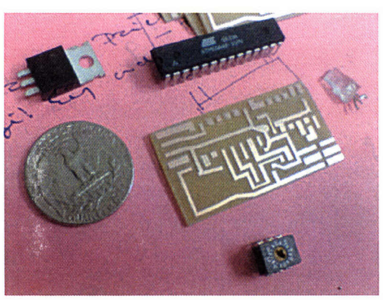
The battery boxes which are also the front and rear axles are brought together with four carbon tubes to form the vehicle body.



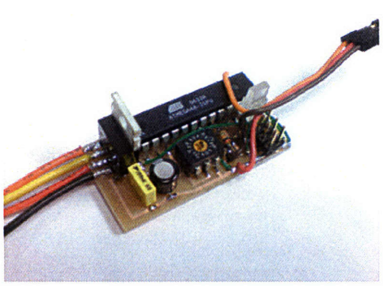
The switches and driver input device jack are mounted.



The circuit boards for the wheel robots and the driver input device are milled using the Modela mini mill.

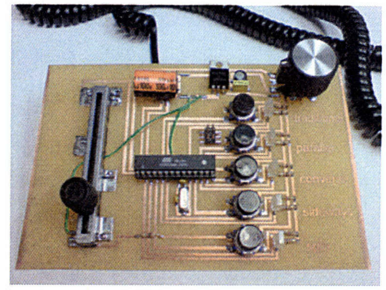


The circuit boards are equipped with parts.

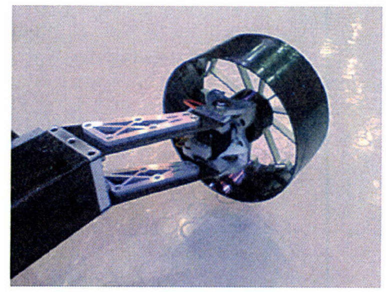


The finished wheel robot circuit board with microcontroller, crystal oscillator, position indicator, programming connector, LED and voltage regulator.

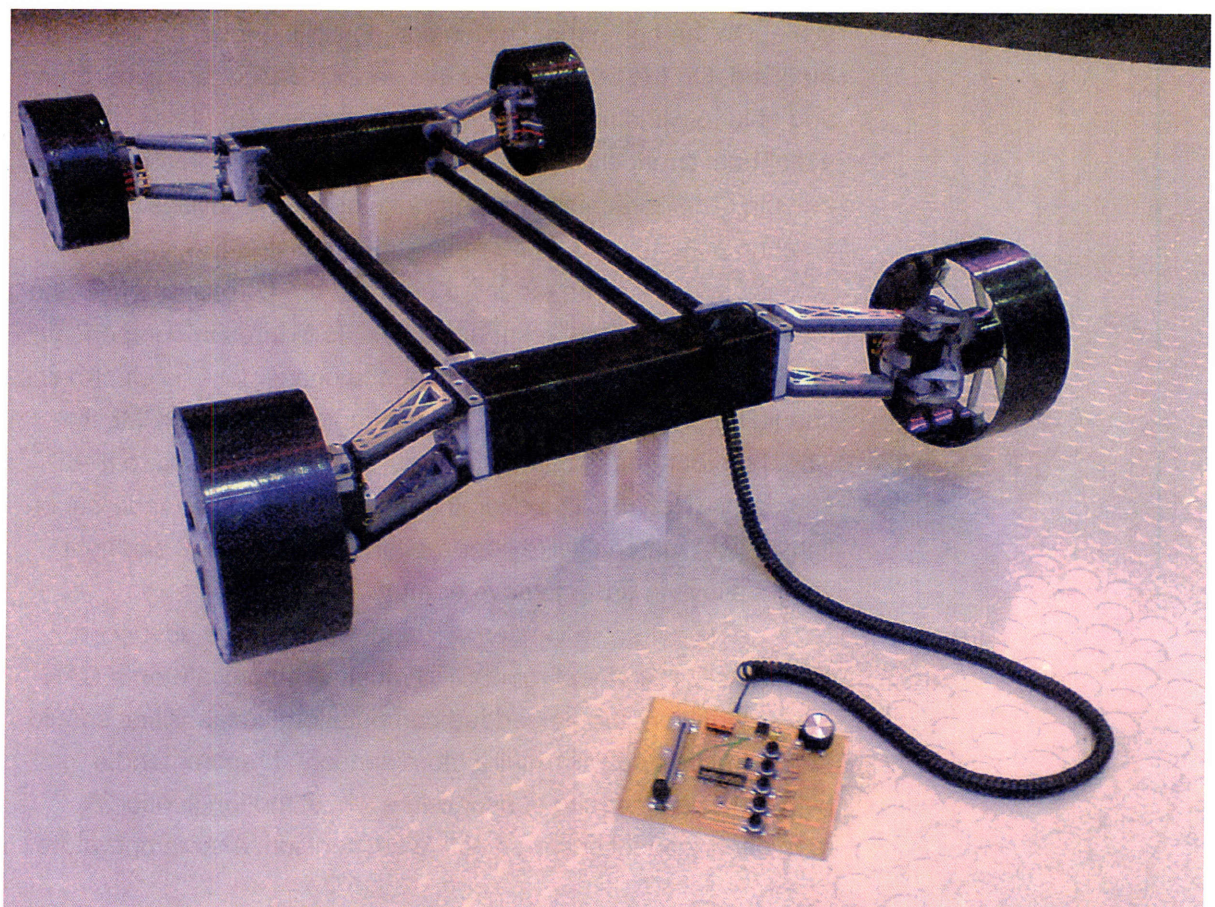
The finished driver input device circuit board with microcontroller, crystal oscillator, throttle and steering potentiometer, drive mode selection buttons, LEDs and voltage regulator.



The finished wheel robot.



The finished half scale vehicle version 2 with driver input device.



Chapter 4: Discussion and Future Directions

The second iteration of the half-scale vehicle presented in chapter 3 convincingly demonstrates a new generation of wheel robots as well as their application in a functional vehicle. The implementation shows that the final wheel robot iteration (iteration 5) is preferable to its antecedents because of its simplicity and multifunctionality. It will, therefore, better serve the needs of the stackable sharable city car and other pure electric or hybrid vehicles. Also this design can be easily fabricated making it a plausible component for the vehicle mass-market. In the following discussion I will discuss each of these strengths and also highlight where further research is needed.

Design Recommendations for a Full-scale Vehicle

The current design will require some modifications at full-scale. On the one hand, certain components should be added or modified. On the other, a full-scale version should be more robust and able to withstand the elements. A damper should be added as a diagonal connection between the double wishbone suspension arms in order to achieve proper suspension capabilities. The steering actuator should be replaced by a piston-like, linear actuator which can be mounted between the connector plate and the motor mounting bracket using flexible fixtures to compensate for suspension motion. At full scale, the connector and electronics should be properly enclosed. For example, discussed PML in-wheel motor already comes fully water proof according to IP 65 standards (Ref 16). The overall structure can still be made out of light weight materials like fiber reinforced composites and light weight alloys in order to save energy.

The full-scale version will also require more advanced electronics. The wheel robot CPU must communicate on a CAN bus. In addition, the embedded computational capabilities should be enhanced and will require more sensors. I recommend a high precision steering sensor and a wheel motion sensor. A road sensor could serve an active suspension. Also temperature sensors should protect the motor and the drive electronics.

Full-scale Modularity

The current design does not make any specifications for replacing a full-scale wheel robot. Because of its spring loaded suspension a wheel robot vehicle must be racked up to release the suspension force before changing the unit. This method is very inconvenient, however, it could be solved with an active suspension or a conventional damper with a lock-out feature similar to a bicycle wheel.

Beyond In-Wheel Suspension

The final wheel robot design shows how a simple, conventional suspension can be implemented without compromising the goals of the wheel robot. Inspired by previous research, the first wheel robot iteration for the electric bike described in chapter 2 attempts to reduce the unsprung and rotational mass of the unit. However, these mechanisms incur significant manufacturing costs and increase the complexity of the overall system a great deal. The final design places the wheel robot connector on the border line between wheel motion envelope which makes it possible to use a proven suspension geometry. I recommend using this approach for future wheel robot implementations.

Ease of Assembly and Manufacturing

Wheel robot 5 utilizes standard parts and reduces the overall number of parts. However, these components are arranged more parsimoniously which increases the effectiveness of the design. For example, simplifying and augmenting the traditional wheel assembly by using the electric motor in three ways eliminates brakes. Replacing pivot joints with flexure joints eases manufacturing processes by reducing the number of components and costs. The only entirely new component is the connector which is placed in a location where traditional cars do not have a connector. However, this connector enables a modular vehicle architecture which in turn also simplifies fabrication by reducing the complexity of the car-body. The absence of an internal combustion motor, a drive train and gear box, a cooling system, a hydraulic system and many more components outweighs the costs of building standardized connectors between wheel robots and car bodies.

Wheel Robots: Ready for Market?

This thesis demonstrates the feasibility of wheel robots for new vehicle architectures. A significant amount of engineering refinement will be needed, but the strength of the concept has been shown. In fact wheel robots are more convincing than any other state of the art electric vehicle drive unit because they will require almost no maintenance. The pure electric, autonomous, enclosed and modular package in combination with a run-flat tire - like the Michelin Tweel - is an outstanding combination. The package contains no liquids or other materials which would need attention on a regular basis because there are no hydraulic brakes, water cooled motors, oil lubricated mechanical parts or inflated tires. Each unit is so “intelligent” that malfunctions, though unlikely, would be easily detected and reported to the driver or service provider.

With all their benefits, these wheel robots enable the customization of vehicles which is an emerging market with great potential. These types of expanded vehicle markets and cultures position wheel robots closer to a consumer electronics than traditional cars. These markets may prove to be significantly more profitable as well. Consumers would buy a second or third set of wheel robots for city and off road driving, or just to have a different car every day. Another scenario might involve a do-it-yourself person who builds her own wheel robot creatures. Also sets of wheel robots can be sold more frequently than new cars.

Not only the wheel robots, but also the body of the vehicle could be exchanged. Fully modular vehicle architecture accommodates rapidly changing battery technology and short lifecycles of energy storage devices because the car body can also be swapped easily. Skate boarders, for example, frequently replace the actual board for fashion, wear or other technical reasons. Instead of buying a new car consumers would select a new chassis which comes outfitted with novel energy storage systems.

(may-be add something about energy consumption)

Vehicle Architecture and a Possible Future

Modular wheel robots have a great potential for future mobility markets and also serve a cleaner and healthier environment. Imagine this scenario for the future: Wheel robots with a standard interface could become consumer electronics products. Battery manufacturers could replace the laptop-sized package with a vehicle-sized package. Car bodies could become sneakers which are custom-made especially for you and soft so they do not harm people. Assembly will take place in a sneaker store while you wait and car manufacturers could earn their profits by selling transportation services rather than one-off products.

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